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Interactivity and Learning: Examining primary school children's activity within virtual environments

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I, Maria Roussou, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

To my family.

And in memory of Professor William Winn, HITLab - University of Washington, who was a pioneer in researching the use of Virtual Reality for Education, and a true scholar.

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Abstract

The two essential properties of a virtual reality (VR) experience, especially in entertainment and informal learning applications, are immersion and interactivity - each of which is advertised widely to attract and motivate participants. In particular, it is commonly considered that a learning environment is more effective if it is interactive. However, little systematic research has been available to substantiate this assumption and no clear evidence has existed that interactive virtual environments (VEs) can bring "added value" to learning, especially in children. This research investigates user interaction in virtual reality learning environments, focusing on the role and the effect of interactivity on learning and change in conceptual understanding. The goal has been to examine whether children learn by interacting in an immersive VE, i.e. exploring, reacting to, and acting upon events.

In this research, empirical studies were carried out with 60 primary school students (ages 8 - 12), in a number of different studies. An exploratory study was carried out to test the methodology and prepare for the main study. The main study, a large scale experiment, was conducted with a VE designed to simulate a 'virtual playground', which focused on a presentation of problems in mathematical fractions (such as ordering fractions). Three conditions - an interactive VR, a passive (or guided) VR, and a non-VR condition using LEGO bricks - each with different levels of activity and interactivity, were designed to evaluate how children accomplish the various conceptual tasks. Pre-tests, post-tests, interviews, video, and computer activity logs were collected for each participant, and analysed both quantitatively and qualitatively. Qualitatively, the descriptive framework of Activity Theory was used to analyse user behaviour in the immersive VR environments and to identify conceptual contradictions, i.e. the occurrence of critical incidents, focus shifts or breaks in the elements of the learner's activity that led to indications of the learner's construction of meaning.

The results indicate that activity based on the cues or feedback provided by the VE led participants to complete the tasks successfully in the interactive VR condition compared to the non-VR condition. Interactivity aided in promoting skill and problem solving and provided opportunities for contradictions to emerge. However, interactivity did not necessarily lead to resolution of these contradictions nor did it ensure that, if resolution was made, this was at the conceptual level. On the other hand, the passive VR form of experience, where the tasks were performed by a virtual robot observed throughout by the participant, showed the potential to support resolution of contradictions in a way that encouraged reflection of the underlying conceptual learning problems. This guided form of interaction, rather than the fully interactive condition, provided evidence of sustained conceptual change.

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Chapter 1

Introduction

1.1 The Research Problem

The main problem to be addressed in this thesis is how user interaction in Virtual Environments (VEs) affects learning. Learning is considered on a conceptual level, as the result of a process of constructing knowledge and of conceptual change. Specifically, the research aims at examining how interactivity and conceptual learning are related in the context of virtual environments developed primarily for young users.

Children represent a large and growing market for interactive products. Indeed, in every new application directed to young consumers, from computer games to educational software, interactivity is being advertised widely, primarily for its recreational potential but also for its significance for learning. This is even more prominent in the case of Virtual Reality (VR), since interactivity is largely regarded as one of the medium's essential properties (Burdea, 2003; Steuer, 1992). It is believed that interactivity in VR (compared to other computer-based multimedia systems) requires particular attention (Stanney et al., 1998), considering the fact that VR adds a spatial, embodied dimension to human-computer interaction, at the core of which is the suspension of disbelief.

The immediate implication which can be drawn from studying the VR literature is the common belief that the effectiveness of a VE that provides a high degree of interactivity is substantially more than the effectiveness of a VE where interactivity is not present. However, little systematic research is available to substantiate this assumption and, to date, no clear evidence exists that interactive VR applications can bring "added value" to learning, especially for children. Hence, a central question emerges: does interactivity, as an essential property of the virtual reality medium, aid in conceptual learning? Does it constitute an effective learning tool?

1.2 Research Aims

The specific aim of this research is to answer the above questions, i.e. to examine the effect of interactivity on conceptual learning in virtual learning environments (VLEs), its potential, and limitations for learning, but also to develop a combined quantitative and qualitative methodological framework for examining conceptual learning in VEs.

In particular, this research questions whether and how interactivity can influence conceptual learning or, put differently, whether interactivity in VEs enables learners to construct meaning and change their conceptions. In order to understand this relationship one must first understand the meaning of its fundamental components by breaking down the above question into further questions: What is 'interactivity'? Who are the 'learners'? What is considered 'meaningful' in the case of learning? These questions are sufficient to indicate that the topic of study is not a simple and concrete problem, but perhaps one in which it could be difficult to achieve measured solutions: the relationship between interactivity and learning is unavoidably complicated and cannot be isolated from the plethora of contextual issues that surround it. A closer look at this context will be developed in the next Chapter, which summarises the definitions, common assumptions, and claims found in the literature while attempting to find answers to these questions.

1.3 Motivation

The motivation for this research lies in the convergence of various recent trends observed in the development of interactive virtual environments, particularly the construction of interactive immersive experiences for the broader public and the increasing role of informal educational institutions in delivering technology-based activities and "learning-by-doing" processes. The deep sense of engagement common in such interactive computer-related activities provides the motivation for a critical examination of the elements that have shown to continuously attract and fascinate visitors, especially children.

Virtual reality, regarded as three-dimensional multisensory immersive and interactive digital environments, has triggered public imagination as the technology that will dominate the way our work, education, and leisure is delivered in the not so distant future. To date, however, immersive VR installations and applications were limited to the scientific visualisation, industrial research, and development worlds. Only recently have we witnessed a proliferation of VR installations (in the form of exhibits) and applications (in the form of "experiences") available to and accessible by the public.

Interactivity is undoubtedly one of the defining components of virtual reality (Burdea, 2003). In the context of a virtual environment, interactivity is regarded as the process through which users can have a first-person experience and can explore, act upon, control, and even modify the environment (Steuer, 1992). The plethoric development of interactive virtual environments for rapid prototyping, industrial design, and training, to name just a few domains, and the evolution of the interfaces, emphasise the appeal of interactivity. Moreover, the proliferation of immersive systems in public spaces, such as museums and entertainment settings, and the growing sophistication of home gaming systems, advertise interactivity as a core attraction of the virtual experience. In all these contexts interactivity is being promoted widely for its effectiveness, motivational impact, and significance for learning (Roussou, 2004).

The entertainment market, traditionally concerned with the creation of spectacles and, nowadays, captivating multisensory experiences, was the first to embrace current technological achievements in the field of VR, in order to advance the "art of experience" both through gaming machines and location-based entertainment. Interestingly, a number of factors contribute to the increasing popularity of advanced digital environments in informal educational institutions (science centres, museums), generally known to be hesitant in adopting cutting-edge digital technologies. Such venues are now adopting or have started to consider various forms of interactive theme park rides (Schell and Shochet, 2001) and multiuser high-end digital theatre experiences (Park et al., 2002) that primarily target young visitors. Recent success stories that exemplify what has also been called "edutainment"[1] or "learning-rich entertainment"[2] include the Hayden Planetarium's 400-seat all-digital dome system at the American Museum of Natural History in New York[3], The Glasgow Science Center's immersive Virtual Science Theatre in Scotland[4], the British Museum's "Mummy: The Inside Story" show[5], the VR Theatre in Korea (the largest immersive and interactive theatre of its kind in the world) (Park et al., 2002), or the cubic immersive (CAVE) displays installed permanently at unusual museums such as the Ars Electronica Center in Austria[6], the ICC in Japan[7] or the Foundation of the Hellenic World in Greece[8] (Roussou, 1999).

Although these are high-cost semi- or fully immersive and interactive installations, it may not be long before scaled-down versions make their way into the schools and the home. Already, the more tactile, kinaesthetic, and gesture-based metaphors of interactivity have been scaled down to consumer products such as the EyeToy[9], while the prominent role of computer games in contemporary childrens' culture drives the market in developing more sophisticated virtual reality applications, in the broad sense. While VR is continually increasing its range of fields of practice and advancing the techniques -and art- of immersive world construction, the techniques for developing interactivity are still relatively unexplored, even though interactivity has emerged as the most inclusive term. The plethoric development of interactive systems confirms Ryan's belief that our culture, formerly one of immersive ideals, is now a culture more concerned with interactivity (Ryan, 2001b). Along the same lines, De Oliveira et al. comment that "in the seventies and eighties, we lived in a society of spectacle, in the nineties in the society of participants, and we are now developing a 'society of interactors"' (De Oliveira et al., 2004). If anything, an experience that does not require a user's participation tends to be rejected as one that promotes a passive and uncritical attitude. It is this recent trend of interactivity and its importance in future sensory-rich virtual reality experiences that provides the motivation for this work. And it is the lack of systematic research to evaluate its effect on learning that calls for studying this issue.

[1] The term "edutainment" is indicative of a growing competition between the entertainment and informal education worlds in attracting visitors. Although it was coined by the computer industry about fifteen years ago, the term has also been adopted by the family entertainment industry in an attempt to "add depth" to exhibits that were made for pure recreation, and thus did not enjoy the credibility inherent to museum educational efforts or educational multimedia. However, as museums and science centres become more popular family destinations and compete in the leisure marketplace, the word reflects an interesting convergence.

[2] Seymour Papert's term from a video interview with Newton Lee, Editor-in-Chief of ACM's Computers in Entertainment, available online at http://www.acm.org/pubs/cie.html.

[3] The American Museum of Natural History, Hayden Planetarium, New York, http://www.amnh.org/rose/haydenplanetarium.html [last accessed: March 2006].

[4] Glasgow Science Centre, Virtual Science Theatre, http://www.glasgowsciencecentre.org [last accessed: March 2006]

[5] British Museum, *Mummy: The Inside Story* exhibit http://www.thebritishmuseum.ac.uk/aes/aesrevrm.html [last accessed: April 2006].

[6] The CAVE at the Ars Electronica Center, Linz, Austria, http://www.aec.at [last accessed: March 2006].

[7] NTT InterCommunication Center, Tokyo, Japan http://www.ntticc.or.jp/index_e.html [last accessed: March 2006].

[8] The Foundation of the Hellenic World's Virtual Reality department http://vr.fhw.gr/ [last accessed: March 2006].

[9] EyeToy, Sony Computer Entertainment Europe, http://www.eyetoy.com [last accessed: April 2006].

1.4 Scope of the Thesis

The goal of this thesis is to examine interactivity and learning in a Virtual Environment. Interactivity is regarded as the activity that takes place between the user and the virtual environment and which, in this case, actively involves the user both physically and intellectually. This research will not be directly examining other properties of virtual reality, such as immersion and presence, unless these are shown to have an effect on the user's interactive behaviour in the VE as far as learning is concerned.

Learning is considered in its development on a conceptual rather than an operational or factual level. Hence, this research will not focus on usability, interface issues, or technical knowledge and skills gained through the use of a VR system. Instead, it will be looking at cognitive change or the increase of understanding of the tasks and conceptual problems, as these have been defined at the outset of each experiment. Following an initial stage of exploration through a study with a small number of participants, described in Chapter 4, a decision to work with learning tasks in the realm of mathematical problems was made, as such problems have proved to be conceptually difficult and too abstract for some children to understand. Furthermore, the learning tasks developed follow the constructivist and situated paradigm of learning by constructing one's own knowledge, as this is considered pertinent to the experiential and active nature of the medium of virtual reality.

This research has been concerned exclusively with children, in particular primary school students aged between 8 and 12. This age group was decided in consultation with collaborating teachers and in accordance to Piaget's assumptions of the periods of development in the evolution of human mind (Labinowicz, 1980). In the concrete-operational stage (ages 7 to 11 or 12), concrete mental models are formed. The child can manipulate numbers, develop concept formation skills and think hypothetically about coordinated action, where two or more variables can be considered at once. This age is, thus, considered to be best suited as a starting point for studying the development of conceptual learning.

Finally, as far as virtual reality technology is concerned, only activity within projection-based immersive virtual reality devices (CAVE-like) was studied through experimental work during this research. The reason is that projection-based (versus head-mounted) displays are increasingly found in real-world contexts, especially contexts that involve the general public, due to their less obtrusive nature. It is hypothesised that projection surfaces, regardless of whether they are stereoscopic or not, will be deployed widely, as the field of Ambient Intelligence (AmI), promoting more pervasive or ubiquitous means of interacting with technology, emerges.

1.5 Contributions

This thesis contributes to the understanding of the complex relationship between interactivity in advanced technological environments and learning, while synthesising knowledge in the areas of human-computer interaction, virtual reality, learning technologies, museum education, and evaluation. Specifically, the contributions of this thesis are:

- The identification of the issues and critical analysis of the literature (Chapter 2) concerning a broad problem domain, that of the educational importance and use of interactivity in digital media at large, and VR in particular. Interactivity is approached by bringing together different areas, from educational technology used within formal education contexts, to informal learning and museum-based environments. This multifaceted analysis of the literature in the different fields and disciplines has identified problems and revealed neglected topics of research, contributing to the overall knowledge of such a specific yet increasingly important property of digital technology.

- The methodological framework, which involves the use of multiple different methods for studying young users' activity in VR, centred around the use of Activity Theory as an analytical tool (discussed in Chapter 3). Typically, Activity Theory is applied to the design of systems rather than as a framework to guide evaluation. This research has adapted, tested, and refined Activity Theory for the evaluation of learning in the context of immersive virtual reality, thus suggesting an explanatory structure for analysing interaction in virtual environments that takes into account the complexity of the problem and the experiential nature of the medium. It, therefore, contributes to extending the application of Activity Theory to activity within virtual environments, thus evolving its use.

- The empirical work through two studies (Chapters 4 and 6) leading to experimental findings (Chapter 7), that provide insights as to how children interact and learn in virtual environments. Specifically, the findings from this research have indicated that the VR experiences were instrumental in maintaining high motivation and focus. The children that performed learning tasks in a VE were able to complete the tasks successfully, aided by the cues and feedback mechanisms that were embedded in the interactive VE. This feedback was able to challenge some participants' conceptions and create opportunities for resolution of prior misconceptions that emerged. However, between the interactive VR environment, which provided the participant with first-person exploration and manipulation capabilities, and the passive VR environment, where the participant observed a robot carrying out the activities, it was the passive VE that seemed to foster a reflective process within the learner and, in some cases, provide evidence of sustained conceptual change.

  Additionally, in order for the studies to be carried out, two virtual environments were designed and created; most notably, the Virtual Playground (Chapter 5), a complex and engaging virtual activity space, which was specifically designed and implemented as a CAVE application for the purpose of evaluating the research questions of this thesis. The Virtual Playground is a standalone virtual reality application which could also be converted relatively easily into a desktop educational software product for learning arithmetical fractions.

1.6 Structure of the Thesis

This thesis represents an account of the research that has been carried out to investigate the role of interactivity for learning in virtual reality environments. This account is developed in eight chapters, beginning with the current chapter, which introduces the research problem, the factors that have motivated this research, the scope, and the contributions of the thesis. The thesis then proceeds with a review of the definitions of the key terms and related work in pertinent areas (Chapter 2), a description of the methodology for data collection and analysis (Chapter 3), a description of the design and analysis of the exploratory study (Chapter 4), the design and implementation of the virtual environment that was used for the main study (Chapter 5), the design of the main empirical work carried out to address the research questions (Chapter 6), the analysis of the empirical study and a discussion of the findings (Chapter 7), and finally conclusions and future work directions (Chapter 8).

Specifically, the next chapter, *Chapter 2*, reviews existing research relevant to the thesis. It starts out by defining learning, interactivity and how interactivity is perceived with respect to learning. It includes a review of various microworlds, simulation environments and other educational technology used in formal and informal interactive learning contexts, as well as a more extensive review of virtual reality projects for education. It draws attention to the lack of systematic evaluation of the effect that specific components that constitute virtual environments may have on conceptual learning. The chapter concludes with a summary of the research that has been carried out so far in the multiple areas, and a summary of the research questions that this research is examining, namely if and how interactivity in a virtual environment enables learning.

Chapter 3 focuses on the methodology adopted both for collecting and for analysing data that address the research questions. This chapter argues for the need to conduct empirical work and proceeds to introducing the experimental design applied to the exploratory study and the main study, described later in chapters 4 and 6 respectively. In particular, the theoretical framework of Activity Theory, used to analyse the observation and interview material collected during the exploratory and main studies, is presented.

Chapter 4 describes the design of the exploratory study. This study, carried out with a small number of participants, served as the first attempt to apply the methodological framework for data collection and analysis. At the same time, the shortcomings of this study, in particular the inability to provide adequate insights into the research questions, are identified and used as a basis for the modification of the approach taken for the main study.

Chapter 5 describes the ways that the shortcomings identified by the exploratory study were addressed, leading to the re-design of the approach taken for what became the main study. This re-design led to the development of a different virtual environment for evaluating the research questions. The new virtual environment, modelled as a virtual playground, was designed to support opportunities for conceptual learning by creating tasks that required solving mathematical fractions.

Chapter 6 describes the design of the main evaluation study carried out in a CAVE-like environment. The experiment conducted as part of the main study included two experimental conditions, an interactive VR condition where children had full control over the virtual playground, and a passive VR (or guided) condition where children observed a robot carrying out the tasks. A non-VR condition was also carried out with children who used LEGO bricks to design a playground.

Chapter 7 presents the analysis of the data collected from the main study, using both quantitative and qualitative methods, as defined in Chapter 3. A discussion of the overall findings and the implications that can be drawn from them is included in this chapter.

Finally, *Chapter 8* summarises the results, draws conclusions, and re-visits the contributions of this research. Possible future directions on different levels and topics are also discussed in this chapter.

1.6.1 Terminology and notation

As noted in Section 1.4, the terms Virtual Reality and Virtual Environments are used in this research to refer to *immersive* virtual reality technology and environments respectively. Consequently, the term Virtual Learning Environments is used to define learning tools or environments that make use of immersive virtual reality settings, and not on-line communities, web-based learning resources, or desktop environments with 3D graphics, unless stated otherwise. Other acronyms used in this thesis are listed in Appendix F.

The words *observer* and *researcher* are used interchangeably to refer to the author of this thesis. The word *participants* is used throughout the thesis when referring to the children that took part in the studies. However, in the exploratory experiment (presented in Chapter 4) the word *subject* is used, in accordance to the Activity Theory terminology. Each participant in the experiments was given a reference ID to aid in the analysis, which consisted of: a code to identify the study (EXP for the exploratory study, PLT for the pilot study, IVR for the interactive virtual reality condition of the main study, PVR for the passive virtual reality condition of the main study, and LEGO for the LEGO condition of the main study), the participant number within the study, the participant's gender ('b' for boy and 'g' for girl), and age. For example, IVR08-b10 means that the child took part in the interactive VR condition of the main study and is a 10 year old boy. In many cases, particularly in the presentation of the qualitative analysis of the main study (Section 7.3), first names are used instead of the IDs for readability. Wherever names are used, these are pseudonyms.

Chapter 2

Background and Related work

The topic of this research, due to its inherently interdisciplinary nature, touches on a number of separate yet intertwined areas that should be explored, synthesised, and translated into practice. The purpose of the literature review is threefold: to gather the definitions, as well as the claims and common assumptions with regards to the topic and identify the areas of research that have not been carried out yet or that need to be filled in; to record the state-of-the-art, current trends and research work in these interrelated fields and to identify their synthesis; and to situate this research by setting the groundwork that will guide it.

Before one can explore the relationship between interactivity and learning and determine if and how interactivity enables learners to acquire knowledge or develop understanding, one must firstly clarify the meaning of the fundamental components of this relationship by providing the common definitions of 'learning' and 'interactivity' and the contexts within which these have been used and studied. In this chapter some of the important terms will be defined by conducting a survey of the related literature.

2.1 Theoretical Approaches to Learning

2.1.1 Definitions of learning

Defining learning is notoriously difficult. There are a range of different perspectives on learning and a great number of theories on how learning takes place[1]. However, learning is still considered a great unknown. Hawkey relates Gardner's polemic on what is known about learning and what remains as yet unknown through a metaphor of learning as being a museum with many rooms. "Suppose that we were commissioned to create a museum of learning," Gardner begins, to conclude that there would be much of interest on display but that several of the rooms would be empty. Hawkey continues the metaphor by adding that if there were a digital equivalent to this museum, a virtual museum of learning, then this would "frustratingly balance myriads of fascinating hyperlinks with numerous error messages and unavailable pages". Moreover, as Falk and Dierking have observed (Falk and Dierking, 2002), most of what is known about learning is based on studies from either classrooms or research laboratories and so may be inappropriate as a basis for considering learning outside of these settings. Much remains to be explored, particularly in non-school settings (Hawkey, 2004).

[1]The online database 'Theory Into Practice' presents and provides references for over fifty different theories on learning, http://tip.psychology.org/theories.html [last accessed: April 2005].

According to one general school of thought, learning is related to behaviour (Reigeluth, 1983). It is the increase in skills, knowledge, understanding, values, and the capacity to reflect. Gaining knowledge, skills, or developing a behaviour occurs through study, instruction, or experience. In other words, learning is a relatively permanent change in behavioural potentiality, that can be measured and that occurs as a result of reinforced practice. At another extreme, focusing on experience, learning is the intellectual process of constructing knowledge, that is, acquiring, assimilating, processing, and integrating information through sociocultural interaction (Kolb, 1984).

The above represent two ends of a spectrum of learning theories, which also encompasses a great number of theoretical debates. These theories, in turn, focus on learners, who represent a rich array of different backgrounds and ways of thinking and understanding. Different ways in which children and adults think and learn have also been identified by a great many researchers and classified into taxonomies of learning styles. Gardner's multiple intelligences (Gardner, 1983), Bloom's taxonomy (Bloom, 1984), Kolb's Theory of Learning Styles (Kolb, 1984) are just a few of these classifications. Additionally, there are definitions for different types of learning (learning of facts, data, statistics, etc; learning of skills, methods, processes, etc; learning of concepts, representations, abstract systems, etc.). For the purposes of this research, learning has been grossly divided into factual and conceptual learning and a choice has been made to focus on the latter.

2.1.1.1 Conceptual learning and conceptual change

Conceptual learning is identified with deeper, transferable understandings of generalisable, abstract knowledge. It has to do with logical thinking, the formation of scripts, stories, cases, mental models or constructs, concepts, associations, perspectives, or strategies (Wiig and Wiig, 1999). Learning how to play chess, for instance, is a highly conceptual task since it involves building mental models, associations, strategies, and engaging in a sophisticated level of problem solving. However, there is no absolute border that divides conceptual from factual learning. As the learning process is being practiced, the novice learner becomes an expert and a shift between conceptual (abstract) reasoning and factual or perceptual processing (to use the model proposed by (Waterworth and Waterworth, 2000a,b)) starts to take place. Learning a new language is a good example of this move from the conscious and abstract to the unconscious and concrete.

This process of change from an existing conception (e.g., belief, idea, model, way of thinking) to a new understanding (Davis, 2001) has been the topic of considerable research across the cognitive sciences, by scholars that offer a large diversity of views about what change means, what are the reasons and mechanisms that produce it, and what constitutes evidence for such change. While the debate continues about how conceptual change takes place, there seems to be no disagreement about whether it occurs; there is general agreement that students carry alternative frameworks, preconceptions, or misconceptions about -mostly scientific- concepts that are robust and difficult to extinguish through teaching (Vosniadou, 2003).

Research on conceptual change has been confined primarily to science and mathematics education because many abstract and non-visual concepts in these disciplines have been shown to cause misconceptions. Children often have non-normative understandings of science concepts. For instance, students often have misconceptions of physical properties that cannot be easily observed, such as the shape of the earth (Vosniadou, 1994). In the humanities, their preconceptions often include stereotypes or simplifications (Donovan et al., 1999). The understandings that children carry can be quite powerful, even early on. For example, some children have been found to hold onto their preconception of a flat earth by imagining a round earth to be shaped like a pancake (Vosniadou and Brewer, 1992). Similarly, many children have trouble giving up the notion that one-eighth is greater than one-fourth, because the number eight is a bigger number than the number four (Gelman and Gallistel, 1985).

A family of theories, methodological approaches, and research traditions has been constructed to explain the origin and evolution of conceptual change as a result of formal and informal learning. This family is composed of distinct and sometimes divergent points of view on how conceptual change happens cognitively, including views on the replacement of misconceptions, conflicts, dissatisfaction with ideas, theory change, category change, restructuring ideas, and others (Davis, 1998). For example, to name a few, conceptual change to diSessa is the cognitive reorganisation in the student's mind of fragmented naive knowledge into complex systems (diSessa, 1988). To Vosniadou, conceptual change is a process that enables students to synthesize models in their minds, beginning with their existing explanatory frameworks. By the time systematic science instruction starts, most children have already constructed a naive relational explanatory structure that makes it possible for them to interpret phenomena. Learning science requires a fundamental restructuring of this, that can be referred to as "theory change". This change is conceived to be a gradual process that can result in a progression of mental models (Vosniadou, 2003). Thus, the views of Vosniadou acknowledge the importance of prior knowledge to learning. Chi believes that conceptual change relates to the repair of misconceptions and that students' ontological categories need improvement (Chi, 1992). In this view, misconceptions are miscategorisations of concepts, so conceptual change is the reassignment of concepts to correct categories. Others speak of knowledge integration as a mechanism of conceptual change. Knowledge integration is the process of linking ideas together to develop a robust, coherent, conceptual understanding (Davis, 1998). Through the processes of knowledge integration -distinguishing between ideas, linking ideas, and identifying weaknesses in one's knowledge- learners revise their understanding of concepts and develop a coherent, integrated understanding. At a different level, Popper espouses that we only really learn by our mistakes -we apply our schemata to the world by living, they fail in various ways and we can learn, change, and develop by modifying our schemata or theories accordingly (Oatley, 1979).

The research on conceptual change has been related to constructivism and Piaget's concepts of assimilation, e.g., the fitting of new experiences into existing mental schemes, and accommodation, e.g., the changing of mental schemes into new ones that are able to explain the world (Posner et al., 1982). As views of learning have evolved from the behaviourist or objectivist tradition to constructivism, social constructivism, and situated action, more researchers have recognised that conceptual change is not something that takes place solely in the individual's mind but a process that can be influenced (facilitated or hindered) by sociocultural factors and educational settings (Vosniadou, 2003). Social constructivist and cognitive apprenticeship perspectives argue that affective, social, and contextual factors also contribute to conceptual change and that these factors must be considered in teaching or designing learning environments that foster conceptual change. Donovan et. al argue that since children already have ideas about the earth and about numbers, ideas such as that the earth is round or that one-fourth is greater than one-eighth, these ideas must be directly addressed in order to transform or expand them (Donovan et al., 1999). Similar views are also adopted by some museum practitioners with regards to informal education contexts (Watts, 2002).

The next section is devoted to an overview of the common learning theories, emphasizing constructivism and situated cognition, which are considered relevant to conceptual change and the kind of conceptual learning sought by this research.

2.1.2 Learning theories

Current thinking about how learning takes place, in both formal and informal educational settings, reflects student-centred learning practices, recently emerging to counter behaviouristic models of education environments. In particular, the constructivist view argues that learners must actively construct knowledge by drawing it out of experiences that have meaning and importance to them. An extension to this principle adds a social dimension to constructivism by arguing that everyday practice is full of dynamic, context dependent problems in need of tools to support high-level human activity. In this section, learning theories which are influencing the design of current educational environments will be reviewed. The purpose of this is to provide an overview of what is being stressed in contemporary educational literature, so it can then be related to the trends in the development of recent virtual reality projects for learning.

2.1.2.1 From objectivism to constructivism

The traditional approach to education reflects the objectivist (behaviourist but also cognitivist) model of programmed instruction, where students learn by accumulating pieces of information transmitted by the teacher. This approach to learning still dominates curriculum and instruction, and is supported by standardised tests. It is recognised in the field of education as instructional design and its goal is to design an educational system that transmits content and skills in a clear, well structured, and efficient manner (Reigeluth, 1983). Dick (1992) defines instructional design as an educational intervention "driven by specific outcome objectives, materials, or procedures that are targeted on these objectives, and assessments that determine if the desired changes in behaviour (learning) has occurred". At a halfway point between objectivism and constructivism, cognitive scientists call for a "mental model", where understanding is seen as an acquisition of a knowledge base as in an expert system model (Duffy and Jonassen, 1992). The goal of the instruction is to help the learner acquire the external information frames and production rules that exist independently of the learner. The goal of evaluation is to examine if mastery has been achieved and that everyone has acquired the same information. Evaluation is thus performed with tests that stand separate from the instruction.

An alternative epistemological basis to this objectivist tradition is constructivism. The constructivist view argues that learning is an active process concerned with learner creation of meaning and the linking of new ideas to current/past knowledge (Duffy and Jonassen, 1992). As far as instruction is concerned, the emphasis is on facilitative environments, rather than instructional goals, where the teacher takes on the role of mentor, or facilitator. Constructivism maintains that because learning outcomes are not always predictable, instruction should foster, not control, learning. Therefore, the goal of education, according to constructivist theory, is to help students construct their own understandings (DeVries and Kohlberg, 1987), thus it involves a large degree of student autonomy and initiative. This has caused a turn to more flexible, open-ended, adaptive, and multi-dimensional instructional techniques as well as more qualitative, observation-based methods of evaluation. Interest in constructivism has blossomed considerably while conventional instruction and assessment techniques have been criticised for their inflexibility (Jonassen, 1988).

Piaget, Dewey, and Vygotsky, each one from a different angle, have influenced the development of constructivist theory which Bruner formulated into a framework for education (Bruner, 1960). Piaget's constructivism is rooted in discovery, play and imagination as fundamental activities for the development of the child's learning (Piaget, 1973; Labinowicz, 1980). Piaget, famous for his research on the psychological development of the child, believed that children have to go through stages in which they accept ideas they may later see as wrong. Understanding is gradually built up step by step through active involvement. Learning occurs and develops through interacting with one's environment, exploring this environment and the construction of knowledge from the experiences gained through this process. Dewey (1966) argued that education depended on action, that children must actively construct knowledge by drawing it out of experiences that have meaning and importance to them. Piaget called for teachers to understand these steps in the development of the child's mind. The teacher's role becomes one of guiding mentor, stimulating initiative, play, experimentation, reasoning, and social collaboration (DeVries and Kohlberg, 1987).

Rooted in Russian philosophy, Vygotsky's theory combines both cognitivism and constructivism. Effective instruction, according to Vygotsky, takes place in the "zone of proximal development" (ZPD), which he defines as the discrepancy between the child's actual development as determined by independent problem solving and the higher level of "potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (Vygotsky, 1978). His views of social negotiation, the social nature of meaning supported by collaborative construction of knowledge, have formed the basis for social constructivism. Learning as understood from the sociocultural perspective is contextualised, situated, and culturally-based (Soloway et al., 1996), recognising the importance of social interaction. Various sociocultural theories have emerged in recent years, influenced by and expanding upon elements taken from the aforementioned learning paradigm of constructivism, namely theories such as situated cognition or cognitive apprenticeship. Also, frameworks such as Activity Theory (AT) have been developed to study learning and activity as these are situated in the sociocultural context.

Seymour Papert calls for further distinction of the constructivist views, by focusing on the involvement of the student in the actual designing, constructing and erecting of "external" products or artefacts (Papert, 1980, 1993; Harel and Papert, 1991). The idea behind using raw data, primary sources, physical, and interactive materials in real-world possibilities is to help learners generate the abstractions that bind phenomena together. Researchers at MIT use the word "constructionism" to describe the knowledge construction process that arises from the creation of meaningful objects (Harel, 1991), that could be anything from physical toys and motors to computer programs or stories. Constructionism has emerged in the last decade as an alternate pedagogy closely related to advances in educational technology. As a result, constructionism is embraced by many educational technologists and this is reflected in the plethora of multimedia and computer-based software that draws upon the constructivist premises. As such, it has provided learning technologists with the theoretical foundations to support the development of open, informal, and virtual learning environments. Many of these are interactive environments for children (see section 2.3.1), as well as Mixed Reality projects where the attempt is made to blend the physical with the virtual by embedding physical artefacts, or 'tangibles', in digital worlds (Rogers et al., 2002).

Some scholars, in an attempt to aid the development of instructional methods that support constructivism, have looked at the commonalities among constructivist approaches to learning to suggest models for designing constructivist learning environments. Jonassen (1988), for example, has stated that purposeful knowledge construction may be facilitated by learning environments which:

- Provide multiple representations of reality and avoid oversimplification of instruction by representing the natural complexity of the world
- Focus on knowledge construction, not reproduction
- Present authentic tasks which provide real world case-based learning environments
- Provide real-world, case-based learning environments, rather than pre-determined instructional sequences
- Foster reflective practice
- Enable context and content dependent knowledge construction
- Support collaborative construction of knowledge through social negotiation, not competition among learners for recognition

The shift from highly guided teaching to a more open learning curriculum is also reflected in the development of technology for learning, namely in the way new digital resources are formed to support teaching and learning methods. In particular, digital learning environments that are designed to be interactive are frequently connected to the constructivist perspective. A substantial body of literature in constructivist learning has been used to back up the development of interactive learning systems, both theoretically and practically. Many of the ideas rooted in constructivism, theories based on motivation and engagement, and frameworks such as Activity Theory (adopted by this research and described in section 3.2.3), can be directly related to the concept of interactivity. Moreover, as virtual reality technologies provide a wide range of possibilities for interactivity and active participation in the formation of the content, they are generally related by researchers to constructivist rather than behaviourist theories.

2.1.2.2 Situating cognition in authentic contexts

The theory of situated cognition regards learning and doing as inseparable, encouraging learning and understanding through continued situated use in the context of an authentic situation. Dewey was the first to argue that one learns through direct experience, by being engaged in authentic tasks (Dewey, 1966). Similarly, Brown, Collins, and Duguid assert that learning is most effective in authentic, or real world, contexts with problems that allow learners to generate their own solution paths. The goal is to prepare students to do the kinds of complex tasks that occur in life (Brown et al., 1989). As a result of bringing students into more authentic learning environments, it is hoped that they will evolve from novices to experts. Other approaches have been labelled as "learning by doing" or "experiential learning" (Kolb, 1984), "guided practice" (Rogoff, 1990), or "anchored instruction" (coined by The Cognition & Technology group at Vanderbilt University (Bransford et al., 1990)). Similarly Varela et al. make the case that all cognition is "enactive", in other words that the way we organise ideas directly reflects how we act in the world. According to this view, cognition is not based on the idea that the mind is a mirror of the environment, but that cognition consists of the constant, reciprocal, interaction between the mind and the environment (Winn, 2003). Lave and Wenger (1991) extend the concept of situated learning by proposing that learning involves a process of engagement in "communities of practice" in which people participate, at first peripherally and then gradually by becoming full participants, in generating meaning in increasingly complex situations.

The role of technology has been considered crucial in supporting this kind of scaffolding and situated use. Using technology to support communities of practice and apprenticeship has thus been a popular guiding principle in many recent approaches to project-based science teaching. In particular, the immersive qualities of virtual reality environments can be closely related to the premises of situated activity, due to their ability to engage the user in a "world" realistic enough to induce the willing suspension of disbelief through simulated reconstruction that preserves attributes of the real environment, such as spatial representation from various frames of reference, physical scale, multisensory cues, etc.

However, criticisms of these perspectives question the definitions of terms such as "authentic" or "learning by doing" in the context of digital simulations. Although some researchers recognise the significance of learning by doing and other learning methods based on activity and practice, they also caution against their potential to cause automatisation and thoughtlessness (Rogoff, 1990). These concerns are particularly relevant to virtual learning environments which seek to provide authentic, activity-rich simulations of real situations intended to support learning that can transfer to real world problems. Specifically, concerns remain about what constitutes an authentic learning environment in the context of a computer simulation and the degree to which such an artificial construct can provide the complexity of real situations, the level of detail and accuracy, the richness of response, and even the aura and the essence of the "authentic" inherent to real environments.

2.1.3 Section summary

This section reviewed the theories concerning conceptual learning and conceptual change, indicating that the notion of what constitutes learning has come to include throughout the years, in addition to the objectivist tradition and the cognitive science approach, constructivism, social constructivism and authentic practice. A connection between the latter perspectives on learning and interactivity has been proposed by researchers, especially in the case of virtual environments that can support active discovery, exploration, and the construction of knowledge in authentic representations of the real world.

Hence, this research adopts the constructivist, social constructivist, and situated traditions of learning. The connections to these theories of learning are further explored in the next chapters and throughout the empirical studies, in an attempt to situate better the relationship between interactivity and learning in a historical, philosophical, as well as practical context.

2.2 Defining Interactivity

Interactivity is a widely used term of great concern to researchers and practitioners in communication theory and human-computer interaction (Steuer, 1992) and the idea of interactivity certainly appeals to the broad public, as indicated by the attention that the term has received over the last few years (Rafaeli, 1988). Despite this interest, there appears to be no consensus on what interactivity actually means and represents; there is no agreed definition, leading to a range of interpretations (McMillan, 2002). What exactly is interactivity? What is the goal of interactivity? Is there one kind or many different types of interactivity?

An attempt to delineate these will begin with the obvious dictionary definitions. The Oxford English Dictionary[2] defines interaction as reciprocal action, action or influence of persons or things on each other. To interact is to act reciprocally, to act on each other, to act together or towards others or with others. This action or process of reciprocal pursuit can take place between people, people and machines, people and software, or even machines and machines. Since this research focuses on the relationship between people and digital environments (machines, software), definitions of interactivity in the context of human - computer environments have been sought. The same dictionary also provides the definition of Human Computer Interaction (HCI), according to which the scope of interaction is limited to information processing and flow of information between computer interfaces and people.

On an operational level, interactivity has been defined as the function of input required by the user while responding to the computer and the nature of the system's response to the input action (Sims, 1997). In practice, and because of the vague use of the term, interactivity is often related to the user's physical input activity, i.e. the mere ability to move a joystick or click on a mouse (Murray, 1997). Steuer regards interactivity as the degree to which users of a medium can influence the form or content of the mediated environment in real time (Steuer, 1992). However, this definition does not entail any form of meaningful response; a drastic and profound influence on an environment can be to turn it off. This involves no meaningful reciprocal action from the environment in the conceptual sense and is generally not considered an interactive capability. Ryan calls interactivity the ability to respond to changing conditions, when the changes in conditions are determined by the user's input (Ryan, 2001a). Joiner (1998) is more specific in distinguishing an interactive digital environment, such as a computer game, from a less interactive system, such as a video recording device, in that the more interactive

[2] Oxford English Dictionary Online, http://athens.oed.com [last accessed: March 2006].

system adapts to the user's actions and allows varied degrees of freedom (viewed as more control over a number of factors such as time, space, "plot", etc.). These definitions of interactivity do well in describing the lower, more operational or kinaesthetic level of human-machine interaction, but do not take into account the social, affective or experiential dimensions that interaction with a system may entail. Hence, widening the scope to broader contexts where the concept of interactivity has been used, such as the informal education, distance education, art, and entertainment fields, was deemed a necessary way forward toward a definition of the term that can suit the purpose of this research.

Indeed, 'interactive' is perhaps the most frequently used word in the publicity of museum exhibits (Hall, 2004). In the context of these kinds of public exhibits where emphasis is given to levels of activity and motivation, Adams and Moussouri define the interactive experience as that which can actively involve the visitor physically, intellectually, emotionally, and/or socially (Adams and Moussouri, 2002). Ryan claims that an interactive medium opens its world after the user has made a significant intellectual and emotional investment (Ryan, 2001b). Artists who have explored interactivity in their digital installations regard interaction with an artwork as the language that articulates the communication between the user and the environment. This is based on an active form of engagement and "the promise of something you do rather than something you are given" (Rokeby, 1998). Hall believes that interactivity is akin to a conversation, and that you can not have a conversation if you are not speaking the same language. For two-way communication to be successful, the user needs immediate and appropriate feedback, and for every possible input there must be a response. In trial-and-error learning, feedback shows the error or the success. Hence, feedback should be designed into any interactive learning experience since without feedback there cannot be interaction (Hall, 2004). Other researchers also consider feedback as being a critical component of interaction (Berge, 2002) and a necessary condition for interaction to occur (Godwin, 2005).

In a similar socially-based context, adopted mostly in distance education and computer-mediated instruction literature (also known as e-learning), interactivity is explained in terms of an individual's active participation in social communication. However, in this case, interaction in learning is seen as something that only really occurs in the interpersonal context (Godwin, 2005). Technology is used to extend normal human interaction across time and space while the interactive aspect takes place among humans rather than between humans and technological systems. This kind of synchronous or asynchronous, online or offline, communication among two or more persons that are, typically, remotely-located is not within the scope of this research. Nevertheless, the distance learning literature has offered the largest body of definitions for the term 'interactivity', as well as a number of taxonomies, modes, and types of interaction (Sims, 1997; Godwin, 2005).

Closer to this research, possibly the most thorough and at the same time practical exploration of interactivity has been carried out by the gaming industry. In the 1980s, the gaming industry had little conception of meaningful interaction[3], thinking of interactivity only as ordered turn-taking in which a

[3]With the exception of early game classics such as 'Adventure' (the first computer adventure game), 'Zork' (one of the first interactive fiction computer games from the late 70s), 'Maze War' (the first networked, 3D multi-user first-person shooter game from the late 70s), and 'Pong' (the famous white paddles that allowed two players to bounce a white square across the screen).

user would push a button and the machine would do something (Stone, 1995). Since then, however, branching pathways, the continuous seduction of multiple choices and the gathering of information in a more or less self-steered manner, have all been interactive functions that most action based games include in their default configurations. More elaborate forms of interaction have also emerged in the online gaming worlds, where many thousands of people playing roles make up the plot as they go, trading and talking, joining or forming factions, and altering the environment, while the system provides a set of parameters, also known as the "sphere of play" (Stallabrass, 2003). Laurel's (Laurel, 1993) view of interactivity as "acting within a representation", inspired by a drama metaphor and the Aristotelian levels of a theatrical play, seems to provide a more appropriate description of the interactive form used in such game playing (Svanaes, 2000).

Surprisingly, interactivity in the context of VR has not followed up on game developments. Whilst interactivity is recognised as one of the most important attributes of VR (Eastgate, 2001), research efforts have been dedicated mostly to advancing specific implementation techniques and not creating comprehensive models for understanding interaction behaviour in VEs (Kaur, 1998). Therefore, very few clear notions of what constitutes interactivity in VR exist and, consequently, not many guidelines have been proposed on how to develop and support it. In some cases, VR researchers have borrowed from other disciplines principles for modeling interaction that can apply to VEs. Kaur, for example, draws from Norman's guidelines (Norman, 1988) of making important object parts visible, making clear how actions are to be carried out, and providing feedback, clear affordances, natural mappings and clear constraints for object manipulation (Kaur, 1998).

Most VR researchers would agree, however, that activity in a VE involves one or more of three forms: to explore the virtual environment by way of navigation, to manipulate virtual objects or elements, and to construct or modify the environment as a whole (further mention of these will be made in the next section). Interactivity, then, in a broad sense, would mean any or all of the above actions on the part of the user that result in a change in the VE (Kaur, 1998), while the degree of interactivity afforded by the VE would refer to how reactive the system is in response to the user's actions. In practice, interactivity in virtual worlds has usually been identified with the ability to choose one's viewing perspective, via a head-tracked system, and position and course within the virtual environment, i.e. to navigate freely via some kind of interaction device. In the more elaborate versions of virtual worlds where features introduced by computer games are simulated, choice is provided from a set of predetermined options with the possibility of -predetermined- ways for the users to change these options. Additionally, the notion of "portals" that transport the user through a set of interconnected worlds has been borrowed from the games discourse. Other than these, manipulative and contributive forms of interaction (see Table 2.1) have for the most part remained unexplored in immersive virtual reality worlds. The focus on primarily explorative forms of interaction in VEs is also implied by some VR researchers who recognise general interaction tasks in VEs to include only navigation, wayfinding, object approach and object interaction (Kaur, 1998).

2.2.1 Types of interactivity

The different definitions of interactivity, as encountered within different contexts, illustrate that interactivity remains a vaguely defined concept, despite its implicit "hands-on" or "physical" nature (Gregory, 1989). Nevertheless, there have been a number of attempts to provide a structure by identifying types, levels, varieties, or degrees of interactivity and modes of interaction.

Sims (1997) has summarised and extended the various attempts and approaches at creating taxonomies for interactivity. These include a basic approach at identifying three levels of interactivity, ranging from *Reactive* (where there is little user control of content structure with program directed options and feedback) to *Coactive* (providing user control for sequence, pace and style) to *Proactive* (where the user controls both structure and content) (Rhodes and Azbell, 1985). In this case and in the context of learning, interactivity was perceived as being extended or improved when the learner had more control, although that control would appear to refer more to navigation than to instruction. A similar finding was concluded through experiments with children completing a virtual task in an immersive VR application where spatial orientation was required (Roussos, 1997).

Contrasting views in the taxonomical debate have identified five levels of interactivity which focused more on the user's involvement with the application and the subsequent effect on learning. The five levels included the modality of the learner's response, the nature of the task, the level of processing, the type of program and the level of intelligence in design (Jonassen, 1988). In relation to these levels, it was also suggested that the level of interactivity would affect whether surface or deep learning would occur. Building on the above, another, more detailed, taxonomy of interactivity developed on three dimensions identifies *Levels* (reactive, proactive, mutual), *Functions* (confirmation, pacing, navigation, inquiry, elaboration) and *Transactions* (keyboard, touch screen, mouse, voice) (Schwier and Misanchuk, 1993). According to this view, the levels of interaction are based on the instructional quality of the interaction, which reinforces the idea that the higher the level, the better the instruction. Heeter has also provided a multi-dimensional conceptualisation of interactivity based on complexity of user choice, effort users must exert, responsiveness to the user, monitoring information use, ease of adding information, and facilitation of interpersonal communication (Heeter, 1989; McMillan, 2002).

Interaction types have also been identified as task oriented, narrative, visual, etc. Important factors that contribute to interactivity include the frequency of interaction, the speed with which content can be manipulated, the range of ways in which content can be manipulated (e.g., the number of possibilities for action at any given time), the ability of a system to map its controls to changes in the mediated environment in a natural and predictable manner, and so on (Steuer, 1992). Seen from the point of view of the machine, various interrelated and overlapping degrees of interactivity have been identified, such as responding to explicit requests in person/machine exchange, perceiving and acting in accordance with non-explicit user needs and requirements, and enhancing exchange and collaboration between people.

In the context of computer games and game narratives, four strategic forms of interactivity are distinguished, on the basis of two binary pairs: internal/external and exploratory/ontological (Ryan, 2001a). In the internal mode, the user projects himself as a member of the fictional world, either by identifying with an avatar, or by apprehending the virtual world from a first person perspective. In the external mode, the user situates himself outside the virtual world, playing the role of a god who controls the fictional world from above. In the exploratory mode, the user is free to move around, but this activity does not make history nor does it alter the plot; the user has no impact on the destiny of the virtual world. In the ontological mode, by contrast, the decisions of the user send the history of the virtual world on different forking paths. These decisions are ontological in the sense that they determine which possible world, and consequently which story will develop from the situation in which the choice presents itself (Ryan, 2001a).

At a minimal level, most of the above attempts recognise gradations of interactivity, with some actions being more or less interactive than others and the underlying assumption being that the higher the level of interactivity, the better the outcome. Although these taxonomies have not been created to help understand interactivity *per se* but to aid designers in implementing interactive applications, they can provide useful starting points for developing criteria to study and understand it.

As far as interactivity in a VE is concerned, Kaur (1998) has proposed a framework to describe the basic flow of *task-based*, *exploratory* and *reactive* modes of interaction in VEs, which includes three models:

- The "Task action" model, describing purposeful behaviour in planning and carrying out specific actions as part of the user's task or current goal/intention, and then evaluating the success of actions.

- The "Explore navigate" model, describing opportunistic and less goal-directed behaviour when the user explores and navigates through the environment. The user may have a target in mind or observed features may arouse interest.

- The "System initiative" model, describing reactive behaviour to system prompts and events, and to the system taking interaction control from the user (for example taking the user on a pre-set tour of the environment).

On a more general basis, interactivity in a virtual environment may entail three levels of activity: on one end, spatial navigation as the lowest possible form of interactive activity; in the middle level, manipulation of the environment or parameters of the environment as the main form of interactive activity; and on the top end, the ability to alter the system of operation itself (where, for example, the user may create or program an environment) as the highest form of interactivity. Similarly, Pares and Pares (2001) have defined interactivity as *explorative*, *manipulative*, and *contributive*, categories which essentially correspond to the above levels of activity (Table 2.1).

For this research, a definition of interactivity will be used that synthesizes several elements from the above taxonomies. Inspired by the informal education context, interactivity is defined as the process that can actively involve the learner physically (i.e bodily movement) and intellectually. This refers to more than a one-to-one process of call-and-response and instead implies multiple decisions and components, as opposed for example to the binary states of turning a system on or off. More practically, the three-word

Explorative interaction	the ability to navigate freely in the VE
Manipulative interaction	the ability to manipulate objects within the VE
Contributive interaction	the ability to alter the environment itself, either in form or functionally

Table 2.1: The definition of interactivity in virtual environments adopted by this research follows the framework presented by Pares and Pares (2001).

definition of interactivity proposed by Pares and Pares (and shown in Table 2.1) provides a general yet concise framework, which contains many of the key concepts of the taxonomies presented previously. Therefore it will be adopted as the central definition for the purposes of this research.

2.2.2 Interactivity and learning

Interactivity is generally regarded as an intrinsic feature of educational practice in the sense of social communication, and an inherent property of any interactive multimedia or virtual reality environment. The value of interactivity is not questioned. Thus, it comes as no surprise that few studies exist that explore the relationship between interactivity, as an autonomous property of a digital environment, and learning. In all cases identified by this literature review, the significance of interactivity for learning is considered indisputable.

There is general agreement among many researchers about the need for interactivity in computer-based learning systems. Barker considers interactivity in learning as "a necessary and fundamental mechanism for knowledge acquisition and the development of both cognitive and physical skills" (Barker, 1994; Sims, 1997). Geoffrey R. Amthor's arguments relating interactivity to activity are summarised in his finding (based on research findings of earlier studies) that people retain about twenty percent of what they hear, forty percent of what they see and hear, and seventy five percent of what they see, hear, and do (Amthor, 1992). These arguments are cited widely in the literature to back up this belief (as is Paul R. Halmos' quote: "I hear, I forget; I see, I remember; I do, I understand"). Seymour Papert, when asked if interactive technology is appropriate for all children, replied that "non-interactive technology is inappropriate for everybody"[4]. Papert's general intellectual position regarding learning has been based on the belief that "the best learning takes place when the learner takes charge" (Papert, 1980, p.214).

Most literature on interactivity and learning is limited to the area of distance education through the use of networks, specifically the Internet. In this area, interactivity is related to communication (person-to-person communication as in teacher-to-student and student-to-student communication) and the examination of the methods, such as interactivity, that constitute the layer of digital mediation. The tools used for such exchange include e-mail, computer conferencing, and different kinds of electronic bulletin boards. In this case, interactivity is regarded as a feature of the medium which allows the user to experience a series of exchanges with it. Interactivity is a means to a greater end -whether that is learning, recreation, completing a work task, or other. In this sense, learning does not occur as a result

[4]Papert at a washingtonpost.com Live Online discussion with Alan Kay, Marvin Minsky, and Allison Druin, during the Interaction Design and Children conference held in Maryland in May 2004.

of interactivity; learning happens as a result of reflection and integration of content into daily thoughts and work/life habits, while interactivity is a tool that (often) leads to this internalization of content.

Steffe and Thompson agree with the views of radical constructivists (mainly with those of von Glasersfeld, 1984) who argue that interaction is an internal construct that leads to a process of cognitive construction: "As an individual interacts in its environment, interactions among constructs within the individual occur as part of the regulation of assimilation and accommodation. In other words, subject-environment interactions can engender interactions within the individual that lead to modifications of the interacting constructs or of relationships among them. These modifications, in turn, can influence subsequent subject-environment interactions, which can engender further modifications of the individual's interacting constructs" (Steffe and Thompson, 2000).

Interactivity has also been studied as one of the factors that can influence the effectiveness of training using a virtual environment. For example, Marshall et al. (2003) report that effectiveness of navigation and spatial information training, usability, and presence was higher when participants had control over their movement within the VE (although control over movement seemed to be regarded as different from interactivity). However, very few studies single out and explore the influence of interactivity on conceptual learning or even question the significance of interactivity as a facilitator of the learning process. Even fewer go further to consider which forms of interactivity, if any, are effective. A study which has tackled this question in the context of geometry teaching with diagrammatic representations, focused on the comparison between different graphical representations of the concept of stereographic projection and the effect that the addition of various interactive properties might have on the learning goal (Otero et al., 2001). For this study, interactivity was regarded as the ability to rotate virtual objects in a VRML space and perceive their spatial abilities, and the ability to manipulate the whole representation or individual elements (for example, to move or rotate the projection line). The hypothesis that the more interactive learning environment would provide better immediate learning results than the less interactive, was tested with four interactive learning environments that used different representations and varied levels of interactivity. The results led to the conclusion that just adding interactivity did not seem to increase the efficiency of the learning environment since the interactive 3D environment did not seem to provide the expected learning gains. However, it was noted that the study was exploratory and additional investigation was required, since learning seemed to be affected by a complex interaction of representations' properties, task demands, and within-subject factors.

Other research studying the effect of alternative graphical techniques for representation in educational software, demonstrated that software which enabled students who were studying modal logic to manipulate and explore relevant representations was more effective at supporting learning than materials in which the representation could not be manipulated (Oliver, 1997). This study further demonstrated that powerful but abstract systems of notation hindered student learning, whereas simpler, familiar representations of "ordinary" objects supported it. This was because students did not have to learn the abstract language at the same time as they tried to learn the concepts being addressed. Another study assessing the benefits of interactivity on the effectiveness of algorithm animation using web-based data structures courseware has shown that, although interactivity has the power to significantly increase the amount of time students spend using such courseware, this added time did not necessarily contribute to increased understanding of the material presented (Jarc, 1999). The results of the experiments indicated that students who used the interactive version spent significantly more time using it than those who used the non interactive version and scored better on several of the questions that tested the more difficult lessons, but performed more poorly overall. One of the explanations used for this was that students found the interactive version more entertaining and therefore spent more time with it, but did not achieve the desired result (i.e. learning the topics). The overall conclusion of this study was the belief that interactivity might be an asset to learning, when properly used.

The fundamental difference between the interactive learning environments used in the above studies and the environments this research is interested in, lies in the use of a different medium. The above simulations and microworlds were developed for a desktop 2D or 3D context, which by default excludes some of the modalities provided by immersive VR environments. These include physical movement and the ability to involve one's whole body in movement, spatial navigation, more natural usability heuristics, and, above all, presence, or the feeling of 'being' in the virtual world. Many researchers believe that interactivity is tightly coupled to presence; or even, that it appears to be the more important factor in engendering presence, both in photorealistic and non-realistic displays (Ijsselsteijn, 2002). Sanchez-Vives and Slater (2005) argue that "the sense of 'being there' in a VE is grounded on the ability to 'do' there". Other researchers regard presence as "tantamount to successfully supported action in the environment" (Zahoric and Jenison, 1998). In relation to education, presence allows total engagement with the virtual environment thus responding to important affective requirements for learning (Winn, 2003). Specifically, studies with students have shown that presence consistently predicts the amount students learn, while positive correlations have also been consistent between presence and enjoyment (Winn et al., 2002).

In addition to the fundamental difference of medium, many of the aforementioned studies are different from this research in that they were directed to a graduate or undergraduate university population, which avoids some of the difficulties encountered in conducting empirical evaluations with primary school children. Nevertheless, some useful points made by these studies can be followed up on for further examination. One can argue, for example, that a problem which emerges from the introduction of interactivity in digital learning environments is learners' seduction with interactivity -they tend to get involved more with the features of interactive systems and thus get distracted from the learning goal. Parallels can be drawn here with similar findings from studying the effect of presence in VR-based learning. Waterworth and Waterworth (2000a) experienced through their studies that, although presence is a strength in educational experiences on a perceptual level in that it activates and motivates ("perceptual seduction arouses the desire to learn"), it may be a weakness for the same reason: the emphasis on the perceptual inhibits the formation of more general, abstract concepts that lead to conceptual learning. Although this interplay of interactivity with motivation and presence in VR may seem an obviously positive formula with regards to learning, the possibility of any negative correlations warrants closer examination.

2.2.3 Section summary

This section reviewed the definitions of interactivity with respect to human-computer interaction and learning. The word interactivity is used widely in connection to technology based systems, with differing meanings depending on the context of use. Different types and levels of interactivity have been identified, while this research has adopted the three-tiered definition of explorative, manipulative, and contributive interactivity within virtual environments, as suggested by Pares and Pares (2001).

A common observation throughout the review of the literature concerning interactivity has been the lack of a critical approach concerning its benefit to learning and, consequently, the lack of systematic research to evaluate its effect on learning, especially in virtual environments. This is also evident in the selection of projects, products, and technology-enhanced learning or play environments, ranging from standard multimedia software to immersive virtual reality worlds, which will be discussed in the next section. Particular attention will be given to the role of interactivity and the way in which it has been used to deliver or support each project's goal.

2.3 Technology-Enhanced Learning

The evolution of the educational theories, from behaviourist to constructivist, described previously, has also guided the development of technology-enhanced learning environments. Hence, the use of digital media for educational purposes has progressed in the past few decades from drill-and-practice software and tutoring systems to more experiential environments that combine learning with play.

During the 1960s and 1970s the focus was on computer-aided transmission, largely involving programmed drill-and-practice methods of instruction. These systems typically presented users with exercises that had to be answered (sometimes within a certain time limit) and then provided feedback on the correctness of the answers. However, in the 1970s Marvin Minsky and Seymour Papert of MIT proposed that research should focus on developing programs capable of intelligent behaviour in artificially simple situations known as microworlds. This concept was supported by the development of the end-user programming language Logo, placing emphasis on learning through the creation of artifacts, which in this case involved computer programming. In the 1990s, the development and widespread use of 3D graphics that could be generated in real time, found its way into educational technology, mostly in the form of computer games. The emphasis shifted to learning to use software packages including applications and educational games.

The evolution of computer graphics and the ability to visualise and manipulate objects, forms, and processes in three dimensions, have brought about a new way of experiencing hard-to-understand scientific phenomena or abstract mathematical concepts. Active exploration and interaction with these objects and forms has been reported to enable the transition from visual experience to a deeper level of meaning-making. Davis and Hersh (1980), after having experienced the computer-generated 3D visualisation of a hypercube rotating on a screen, reported being impressed by how it looked but rather disappointed by the medium's lack of potential to support further meaning making. However, when taking up the controls and interacting with the computer visualisation, they claimed to be able to experience dimensions beyond the three of space and one of time that one normally experiences: "I tried turning the hypercube around, moving it away, bringing it close, turning it around another way. Suddenly I could feel it! The hypercube had leapt into palpable reality, as I learned how to manipulate it, feeling in my fingertips the power to change what I saw and change it back again. The active control at the computer console created a union of kinesthetic and visual thinking which brought the hypercube up to the level of intuitive understanding".

The 21st century has seen the advent of ambient intelligence, evolving the form of the computer as we have known it to a "disappearing" computer, i.e. a distributed, pervasive, mobile, emotion-inducing, and sensor-driven set of devices that strive to be seamlessly interconnected through natural interfaces and interaction metaphors. The technology to support educational practice has started to escape the screen, embedded into all kinds of physical objects, appliances, mobile phones, music players, and game consoles, or ubiquitously spread indoors and outdoors into mixed reality and augmented reality spaces. An increasing number of national and international projects and collaboration networks, such as EQUATOR[5] and Kaleidoscope[6] have been formed to investigate and advance the concepts, methods and technologies of this newly emerged and future vision in interactive learning systems.

Although many strong claims have been made for the power of educational technology throughout the previous decades, many believe that there has not been corresponding evidence documenting positive cognitive consequences of exposure to computer-based learning environments (Cognition and Technology Group at Vanderbilt, 1996). Jonathan H. Fanton, president of the MacArthur Foundation and responsible for funding a recent programme titled "Digital Kids"[7] has also pointed at the lack of systematic evaluation. "Common sense", he argues, "suggests that exposure to digital media affects young people in formative ways, reflected in their judgement, their sense of self, how they express their independence and creativity, and in their ability to think systematically. So far, there is little empirical evidence to back this up."

Interactivity has played a core role throughout the evolution of educational technology, itself evolving from the initial clicking on a button to advance through a set sequence required by programmed instruction, to permitting users to create the educational content themselves. In the following sections, different computer-based interactive learning environments are reviewed, providing an overview with a representative sample of the ways in which interactivity has been used, misused, or not used to support the learning goals set out by these environments.

2.3.1 Interactive learning environments for children

The digital revolution is witnessing an increasing number of project efforts and software products that are directed to children and students, across a wide spectrum of environments, from microworlds to immersive virtual worlds. Interactivity has been, in different ways, the driving force behind microworlds,

[5] EQUATOR, http://www.equator.ac.uk [last accessed: April 2006]

[6] Kaleidoscope, http://www.noe-kaleidoscope.org/ [last accessed: April 2006]

[7] UC Berkeley-USC "Digital Kids" project, http://www.berkeley.edu/news/media/releases/2005/04/14_youthdigitalmedia.shtml [last accessed: May 2005].

experiences and hands-on exhibits found in informal education contexts, and virtual learning environments alike.

2.3.1.1 Microworlds, simulation environments, and participatory design processes

The most prolific content areas of educational technology have been the fields of science and mathematics education. For mathematics education, computers have been used as educational media in the form of microworlds, simulations games, and tutorials (Kaput, 1992). Microworlds are rule-based, computational environments which a learner uses to experiment, explore and construct within a coherent conceptual domain. They are contained environments that simulate various phenomena or processes based on "the notion of computer feedback" and "characterised by the representations of ideas, objects and phenomena on the screen." (Godwin, 2005). Hoyles et al. (2002) view microworlds as spaces where the learner, through playing, may "stumble over and then ponder important inspirations and concepts".

Examples of simulation environments are projects such as SimCalc and products such as SimCity. In SimCalc, the researchers attempted to provide visualisations "as a window onto complexity" by developing simulations that would enable middle-school students in inner-city classrooms to outperform suburban high schoolers in learning calculus (Kaput et al., 2001). In SimCity[8], a well-known simulation game not directly educational nor necessarily intended for children, the user engages in the construction of a city and the relationships this entails. The operation of the simulation system requires a god-like position of power, but, at the same time and in order to increase dramatic interest, the system casts the user as a member of the fictional world (Ryan, 2001a). The notion of interactivity, manifested by the very active role of the player in constructing her ideal city, is based on control.

In this sense, the most interactive simulation environments for education have been the ones that provide their users with the highest degree of control: their ability to construct their own programs. This constructionist approach encourages end-user participation in the design and development of a learning product through the use of programming systems and has been the central concept behind Papert's Logo (Papert, 1980). Subsequent projects by Kafai (1995) and Harel (1991), in which children designed and programmed games or instructional material for other children, have advanced the notion of self-constructed computerised artifacts. This is also the idea behind simulation-authoring and programming languages for children such as KidSim or Cocoa (Cypher and Canfield Smith, 1995), Squeak[9], and ToonTalk (Kahn, 1996), which have also been used in classrooms to enhance maths and science learning. The latter has been used specifically for mathematics learning in the Playground project, a computational environment in which children between 4 and 8 years of age could collaboratively construct, modify and share computer games using the underlying models for the games as creative tools in the process (Hoyles et al., 2002).

2.3.1.2 Interactive environments and the informal education context

An interesting approach to exploratory and free-choice learning has been the development of digital storytelling environments. In storytelling environments, interactivity is based on creating and experiencing

[8] SimCity, http://simcity.ea.com [last accessed: April 2006].

[9] Squeak, http://www.squeak.org [last accessed: April 2006]

a combination of physical and digital spaces that are structured by a participatory form of narrative. A successful example of a multi-person, fully-automated, interactive, narrative environment, the KidsRoom (Bobick et al., 1999), was designed as a play space using non-encumbering sensors to deliver images, music, narration, light, and sound effects in response to children's actions. In KidsRoom, children were guided through a reactive adventure story, encouraged to construct and manipulate aspects of the physical environment in order to create and listen to the story as it developed. Its creators note that children in these environments are more open to explore, experience, and move than adults (Rogers et al., 2002). Other initiatives include KidPad, a "zooming" tool that enables children to collaboratively create stories (Stanton et al., 2001), KidStory, multi-user story creation and story telling tools for large groups of children involving tangible technologies embedded with computational and communication capabilities (Bayon et al., 2003), and GhostWriter, a virtual role-playing environment designed for educational drama development and writing instruction (Robertson and Good, 2003).

Characteristic of a challenging interaction design case is the MEDIATE project, which involved the design of an interactive installation for children 6 to 12 years of age with severe autism and no verbal communication (Pares et al., 2004). One of the basic concepts behind the design of MEDIATE was to provide the children with clear interaction "dialogues" that would give them a sense of control of the system. Thus, an environment approach was chosen, as these children could easily adapt to a full body interaction (e.g., by simply moving through the defined space) to which the environment could respond by generating responsive visual stimuli. The results report that almost all of the children entered the space, found at least one of the proposed interactions, and successfully played with it for a duration from 5 to 35 minutes. However, an evaluation of whether the children acquired the intended sense of control within the environment thanks to the designed interaction has not been reported.

These interactive environments for young children have emphasised the value of manipulative materials and open-ended forms of play, aimed at enhancing interactivity and engaging children in complex ways of thinking and acting. The learning goal in the design of many of these environments has been to enable the occurrence of "unexpected events, novel reactions, novel activities, and novel combinations of activities or events, which in turn facilitate children to question them and to reflect on their experiences" (Rogers et al., 2002).

Due to the open nature of environments such as the ones mentioned above, their application is more likely to take place in the context of informal education institutions, i.e. museums and institutions that carry out their own educational activities independently of the formal schooling system. In contrast to formal education, where learning goals are set to specify instruction with specific learning outcomes, learning from informal educational activities is emergent rather than set. Originally, museum educators attempt to define learning goals or learning outcomes by drawing experience from classroom environments. However, these goals can be very specific and ambitious for informal settings, while they are rarely designed to apply recent research on free-choice learning outcomes. Hence, more exploratory exhibits and environments that aspire to the constructivist learning perspective are increasingly being developed by the informal education context.

The largest body of research in interactive exhibits and spaces comes from museologists' research in science centres and children's museums (Moussouri, 1997; Ramsey, 1999). Having explored the value of interactivity and active involvement ("hands-on" and "learning-by-doing" approaches) in the design of their curricula and exhibits, these learning contexts have dealt with many of the issues concerning interactivity and learners/learning (Thomas, 1994; Thier and Linn, 1976; Adams and Moussouri, 2002; Watts, 2002). Additionally, a particular set of relevant issues applies to these contexts concerning the practice of museum-based education in general, and the observation of visitors with interactive exhibits and interactive new media systems and processes (Eason and Linn, 1976; Hein, 1987; Falk and Dierking, 1995, 2000).

There is also a strand of research concerning computer-based interactive environments that do not directly target learning purposes, such as the growing number of artistic new media projects or location-based entertainment and theme rides. These environments place great emphasis on the relationship between user/audience/visitor and technological medium. Of particular interest are environments that are exploratory, experience-based, or require action from the user that may be unconventional, creative and expressive. Furthermore, in some cases there is said to be an emphasis on "meaningful" interactivity, in the sense that the user's interaction with the environment may count in shaping the entire experience and essentially forming the interactive work (i.e. the work of art does not exist without the visitor's participation). Museums such as the Ars Electronica Center in Austria, the NTT InterCommunication Center in Japan, the ZKM in Karlsruhe, Germany, and an increasing number of media centres, support the development and collection of such work. However, as mentioned, this work is usually not designed for educational purposes.

In the case of Virtual Reality, there are limited public settings in which the educational application of interactive VR can be established. Informal public education centres are currently the spaces that are most likely to include or adopt emerging media such as VR in their practice. This model of public experience centres is becoming more and more popular with visitors, who seek to enhance their free time with engaging activities that incorporate educational value. As mentioned at the outset, the context and drive to take on this research is motivated by such proliferation of interactive virtual environments that are accessible to and sought by the broad public.

The exploration of virtual space through navigation has been the dominant model of interaction in virtual environments targeted for public presentation. The difficulty, on both a technical and a conceptual design level, of incorporating other forms of interaction has prevented designers of informal education spaces from exploring more exciting and innovative models of communication with the virtual world. Interactivity is largely restricted and difficult to apply in a public space, especially when the practical difficulties of visitor throughput and other complications must be overcome or when more than one user must share the same screen (Robinett, 1994).

The Hayden Planetarium's 429-seat all-digital dome-shaped virtual reality simulator at the American Museum of Natural History in New York has attracted millions of visitors in the now six years it has been open to the public; however, the experience resembles a traditional planetarium show and interactivity (although possible with the real-time equipment of that particular installation) has yet to be explored and made available to visitors. Other planetaria are struggling with similar issues. In fact some venues, such as the Eugenides Foundation digital planetarium[10] in Athens, Greece, which has been operating for the past three years, has installed from the start three-button devices on each one of its 280 seats but is still reluctant to produce an interactive show, fearing that any departure from the traditional successful recipe of the linear show will confuse visitors of its educational goals and distract young audiences[11].

A much smaller-scale immersive VR science exhibit in the form of a curved screen opened to the public at The Glasgow Science Center in Scotland. The Virtual Science Theatre started by showing 'The power of the machine', a twenty minute introduction to how VR technology is applied in the design, medicine and simulation industries. As with every new installation of this type, the safe route of a pre-rendered passive show was chosen and interactivity, although possible with the real-time technology these theatres are equipped with, is not being explored. No reports on the Virtual Science Theatre's operation or planned programmes are available.

Perhaps one of the most successful cases of a high-end stereoscopic virtual reality show for the broad public has been the "Mummy: The Inside Story" exhibit, which ran at the British Museum in London from July 2004 to January 2005, and has been touring other museums since. A 112-seat immersive theatre with a 12-metre curved screen display was installed in the British Museum's special exhibitions gallery, along with a pre-show area with small screens on which the story of Nesperennub, a priest from Egypt's religious complex of Karnak who was mummified 2800 years ago, was introduced. Once in the virtual reality theatre, visitors put on paper 3D glasses and were taken through a 20-minute stereoscopic virtual reality experience of uncovering Nesperennub's wrappings, learning about the world of ancient Egypt and the practice of mummification. The experience was a passive documentary-style tour led by a voice, while interactivity was deliberately left out of the scenario.

The largest of its kind immersive and interactive VR theater in the world built for the Kyongju World Culture EXPO 2000 in Korea (Park et al., 2002) was more an entertainment experience than an educational centre, promoting a new kind of cultural tourism. The VR theater was characterised by a single shared screen and user input keypads attached to each one of the 651 seats of the theater. Real-time computer-generated imagery was projected in stereo on the large curved screen, with 3D audio, vibration and olfactory elements enhancing the immersive setting. At certain predefined moments of the virtual guided tour, the audience was prompted to control parts of the experience, such as the movement of butterflies, by using the keypads. The sheer size of the audience, not to mention all the practical challenges this evoked, forced a method of tight control over the design of the interactive parts and excluded any meaningful interaction or control on an educational level.

On a smaller scale, interactivity has been explored also for cultural heritage education at the Foundation of the Hellenic World's (FHW) cultural centre in Athens, Greece (Roussou, 1999), where two immersive VR installations, a single-screen ImmersaDesk^{TM} and a CAVE-like cubic immersive display, have been open to the public since 1999 and continue to receive over 200 children a day who visit

[10] Eugenides Foundation http://www.eugenfound.edu.gr/ [last accessed: March 2006].

[11] Relayed to the author by the Planetarium's director, Dr. D. Simopoulos, during personal communication.

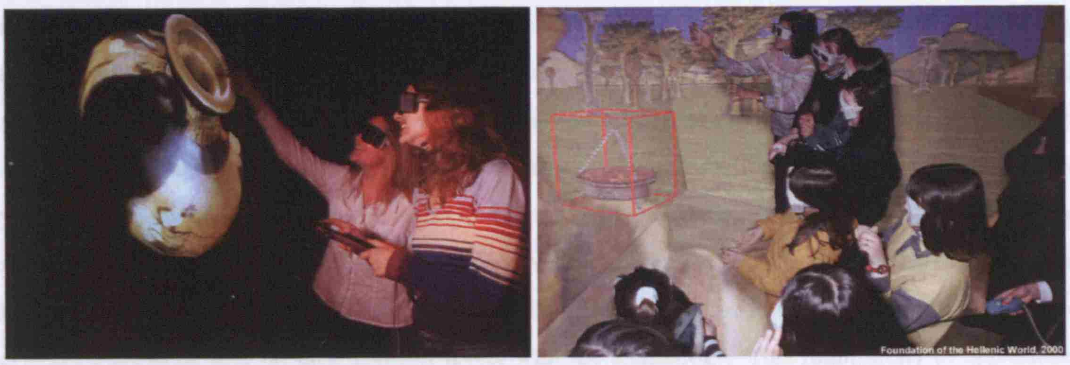

Figure 2.1: The interactive virtual reality programmes developed and presented to the public at the Foundation of the Hellenic World follow an approach where human guides (museum educators) control and decide how much and what kind of interactivity to provide to their visitors. This has shown to be essential in public settings in order for the audience to gain a deeper understanding of the content while having fun. Foundation of the Hellenic World, 1999-2002.

the cultural centre with their school. The VR programmes, presented as 10-minute "shows" to a group of 10 visitors at a time, range from highly detailed reconstructions of ancient cities that are experienced as virtual tours with the guidance of a museum educator, to interactive environments that require more active visitor participation (such as the 3D puzzle-like construction of pottery by connecting virtual shards). Informal observation of the children's response to the VR programmes at FHW has shown that the interactive programmes, when used as such, are considerably more interesting and exciting, with tremendous potential of becoming truly successful educational material. At the same time, they can cause a number of practical difficulties (for example, delayed visitor throughput and the formation of larger queues), which ultimately succeed in making interactivity undesirable for the museum. On the other hand, the virtual tours and architectural walkthroughs, despite their elaborate 3D graphics production, seem to fall short of children's expectations, if not combined with an element of fast action, direct control or surprise, such as diving into the harbour of the ancient city to swim with the dolphins or flying through the fire of the sacrificial altar. These "tricks" were devised as means to strengthen the engagement level (since the novelty factor showed to partially wear off by the end of the 10-minute passive walkthrough experience) and to consequently aid in drawing interest to the learning topics (Roussou, 2006).

The role of the museum educator, guide, or facilitator as mediator is crucial as to how interactivity is perceived by and available to the visitors of the cultural centre's virtual reality programmes. The museum's mandate has been to send its visitors "back into time" as part of a wondrous as well as informative experience of Hellenic history. The museum educators have thus been trained (by this researcher) to use the VR devices and treat the systems as time machines, presenting the historical facts while navigating through the accurate virtual reconstructions. All interactive features programmed into the virtual environments, such as the ability to pick, place, and rotate objects, connect pieces of vases together, resize elements, use the interaction device as a paint brush to reveal frescoes or even create molds for the statue of Zeus in Olympia, are performed by the museum educator and verbally explained to the visitors. The use of museum educators as guides in the virtual experience not only helps "externalise" the learning concepts built into the experience but promises the development of a unique "show" every time. In this way, the museum can maintain the potential for multiple, different experiences that respond to visitor needs rather than a single, repetitive, identical experience. The interactive experience is thus controlled by a human mediator who juggles the multiple roles of user, presenter, educator, and performer, taking into account the age, style, and dynamics of each visitor group and the practical issues of timing and throughput (Alexaki, 2006). Different guides employ different methods of structuring the visitor experience, depending also on their comfort levels with the technology. This multiplicity of approaches also means that the visitor experience depends on the skills, charisma, will, or even fatigue of the educator/guide, in the sense that even unpredictable external reasons ("having a bad day") can change the quality of the experience dramatically, making it inconsistent. Hence, the interaction varies with the guides' preferences and capabilities: some may choose to keep exclusive control of the interface and others to share the controller among all visitors; some prefer to direct the experience, others to suggest possible courses of action; some encourage interaction, while others prefer a more structured experience; some use the experience as a way to generate questions from the visitors, others as a vehicle for dramatic improvisation and magic. This is considered the ultimate interactive process, facilitated by the virtual environment, but contextualised and completed by humans (Roussou, 2004).

An attempt to blend educational goals with entertainment (also coined "entertainment education") was developed by the Immersion Institute and Immersion Studios Inc. with support from the JASON Foundation for Education[12] in an interactive show titled "Exploration: Sea Lions". The show, which ran at three different museum and science centres for a duration of two weeks, aimed at teaching students about the life cycle of aquatic mammals by engaging them in a process of scientific inquiry (Ritterfeld et al., 2004). In order to accommodate the two educational goals that required both the group's (entire class) and the individual student's participation in the experience, a big screen / small screen interplay was developed, combining a movie-like cinematic experience with computer game playing: the cinematic presentation provided the narrative while the individual small consoles offered the interactive capability of communicating with an "expert scientist" to solve a problem, through the development of hypotheses and answers to factual questions.

As evidenced by these example, the design of interactivity for a museum VR exhibit has the challenge of preserving a balance among individual and group experience, educational impact and high motivational and engagement levels, and seamless, natural, and customised modes of interaction. Ultimately, interactivity must be designed to encourage visitors to engage in and question the content, while at the same time avoiding the danger of a confusing and fragmented experience. Museum practitioners recognise all too well that creating technology-based interactive experiences can be a daunting prospect. They are costly, highly technical and present a myriad of design, development and evaluation issues. There also is the constant challenge to create environments that facilitate learning rather than simply entertain (Hall, 2004). The difficulty of incorporating interactivity in VR productions explains why in the most

[12]*Immersion Institute's Exploration: Sea Lions*, http://mysticaquarium.org/divein/immersion/immersion.asp and http://www.jason.org [last accessed: April 2006].

successful examples of highly interactive virtual environments targeted to the public, the creators have engaged in a sophisticated engineering of the illusion of interaction, either by employing human mediators or by programming sequences of controlled interactivity through an intelligent approach to providing system response mechanisms (Roussou, 2004). In the latter case, the choices that the user makes and the attempts to modify the world or cause a response are usually directed by a set of predefined options that are determined by the creator. In the location-based entertainment world, examples that demonstrate mastery of what Schell refers to as "indirect control" (Schell, 2003) include the DisneyQuest[13] virtual reality attractions of Aladdin and Hercules, and the final adventure developed by DisneyQuest in virtual reality, the Pirates of the Caribbean (Schell and Shochet, 2001). In all these cases, visitors assume the roles of central characters in the story and, for the 4 to 5 minute duration of their experience, believe they control the progress of the story, which is rapidly building to a climax, when in fact every aspect of the experience has been carefully and intelligently planned in advance. These methods of incorporating interactivity in a virtual world are essentially based on the qualitative experiences that users equate with interactivity and their *perceived* interactivity of the environment or system (McMillan, 2002).

2.3.2 Virtual Reality in education

The use of VR in education is a relatively new area, counting a little over a decade of development. The area seemed to reach a peak in the mid 90's followed by a slowdown in activity and funding for projects thereafter. In this period, a number of different projects have been developed that span the spectrum of learning domains, from the more concrete to the more abstract and exploratory. This process has also brought a level of maturity and, while our understanding of learning through the use of VR as an educational medium is still in its infancy, a small core of high quality research work and theoretical frameworks have emerged, as well as an interest in the engineering and computer science communities in education as a legitimate arena in which to develop and test VR applications[14].

Researchers in the field have been advocating examples of the value of VR as a medium for interactive, collaborative, and engaged learning. Virtual environments have been valued as being extremely motivating for learners (Bricken, 1991), especially for those with non-traditional learning styles. Salzman et al. cite three promising features of VR with respect to learning: three-dimensional immersion, multiple frames of reference, and multisensory cues (Salzman et al., 1999). Ongoing efforts at characterising phenomena such as immersion, presence, and realism are beginning to clarify their effects (Winn, 1993; Slater and Wilbur, 1997; Marshall et al., 2003). VR affords opportunities to experience environments which, for reasons of time, distance, scale, and safety, would not otherwise be available to many young children, especially those with disabilities (Cobb et al., 2002a; Strickland, 1996; Cromby et al., 1995). Early exposure to virtual environments is believed to both leverage the well-known efficiency and capacity of children's learning and provide advance organisers for later learning experiences. Even usability issues seem to present more of a problem to adult VR users than children, who both easily adapt to graphic and conceptual abstraction (in cartoons and comics) and who often have extensive experience

[13]DisneyQuest Indoor Interactive Theme Park, http://disneyworld.disney.go.com/ [last accessed: April 2006].

[14]As argued by William Winn and Nick Hedley in their call for submissions to the special issue of Springer's Virtual Reality Journal "Using Virtual Reality in Education", December 2005.

in navigating 3D spaces and discovering and exercising interface affordances (Provenzo, 1991).

Critics, on the other hand, warn that, while highly responsive interactive virtual environments can provide immediate feedback and be extremely motivating, they may also encourage automaticity and lack of problem solving (Collins et al., 1996). Moreover, there is belief that much of this engagement is due in part to the novelty effect and is not necessarily inherent in the design of the learning environments.

Despite these views, research projects, for the most part, have adopted VR as a means to access and present information in innovative ways for learners. Additionally, new developments such as telepresence, the integration of VR and high-speed networking, promise new possibilities for distance learning and the exploration of social behavior (e.g., cooperation, conflict) amongst remotely located learners who share the same virtual space.

In a 1998 report by the Institute for Defense Analysis (Youngblut, 1998), Youngblut comprehensively surveys work over the past few years in the area, citing approximately 50 VR-based learning applications. Different types of virtual worlds were identified, ranging from a simple virtual environment with text, no audio, and one observer (which were, however, excluded from Youngblut's report), to environments that are more complex, containing sophisticated computer graphics, audio, multiple users, and interaction with objects and avatars (i.e. virtual entities representing other humans).

Based on the above, the virtual reality environments which are designed specifically for education typically fall into categories that coincide with the type of VR technology used. The first includes networked on-line virtual environments, which are considered to be highly interactive -in the sense that interactivity is based on communication- but not immersive. In a learning context, these environments have been used primarily for the purposes of distance education. The second involves low-cost virtual reality simulations that can be used in the classroom on desktop systems, in which case interactivity varies according to the control given by the programme and immersion also varies but is not easily provided. The third category includes the larger-scale immersive VR learning environments, where immersion is high and interactivity depends on the programme and complexity of the virtual world. This variety of virtual worlds has explored, at different levels, the properties of "presence" and "immersion" (generally confused as being the same thing -for a clarification of the terms, see (Slater, 2003)), but less so the property of "interactivity".

The following sections will present an overview of educational VR projects that are categorised along these lines. A brief mention of on-line virtual worlds and desktop VR projects will be given, followed by a more extensive report on the projects involving immersive VR technologies, especially those that target elementary and middle school children.

2.3.2.1 On-line networked virtual worlds

On-line text-based environments, VRML-based worlds, Active Worlds communities, and other similar environments consist of real-time multi-person virtual worlds that are based on networked collaborative activity. The earlier examples of these worlds were created with text descriptions rather than graphics and are commonly known as MUDs (or Multi-User Dungeons) and MOOs (MUD Object Oriented, a MUD where users define spaces and objects). Developed from on-line environments that allow several participants to play a computer game of Dungeons & Dragons together, MOOs and MUDs support real-time interactive use among a large number of concurrent users that may be sitting at remotely located computers but sharing the same virtual world.

These text-based virtual environments were primarily designed for entertainment, but an increasing number of MUDs and MOOs started appearing for education. One of the earlier ones, ExploreNet, was a networked virtual world where children interacted with each other via avatars in settings filled with computer-controlled props. ExploreNet employs a story-like two-dimensional graphical interface to combine networked use of text and graphics, with a goal to facilitate the creation of habitats in which virtual communities of learners and mentors interact (Hughes and Moshell, 1997). The Grassroots project was a popular text-based simulation of a neighborhood in a MOO combined with a WWW page. Students from around the world recreate their neighborhoods and share them with others (Parsons and Zenhausern, 1996). A more "traditional" MOO was Moose Crossing, an improved version of the earlier MediaMOO project, designed for children to program objects and their behaviors (Bruckman and Resnick, 1995). A few other MOOs have been developed for teachers, such as Diversity University and Deadalus MOO, but most of them are more loosely defined and function as forums, or "chat rooms", where issues of self expression, identity, social interaction, and cultural awareness may be explored. Recent on-line 3D worlds, which are visited by hundreds of thousands, such as Active Worlds[15] and SecondLife[16], have made spaces available for educators to create "globally networked virtual classroom environments" for experiential learning, allowing individuals to practice skills, try new ideas, and discover new paradigms in social learning.

The advocates of these VR environments for education cite two virtues: the creation of a community context and the encouragement of reading and writing (especially in the text-based worlds). The sense of community inspired by these environments allows the exploration of social codes, power and group dynamics. The fact that the communication structure is built through the use of "chatting" and navigation of low-quality graphical worlds supports the second argument. An interesting aspect of these types of virtual worlds is their strong connection to narrative and the area of Interactive Fiction (IF), as participants can assume various identities, develop situations cast in story-like or adventure-based formats, and interact with objects and characters. In this case, the machine acts as facilitator of playful and potentially dramatic human interaction and dialogue, which can, in turn, foster a society based on discourse and collaboration (Murray, 1997). Robertson in her research with the game Ghostwriter, in which textual communication between players was crucial to the decision-making process, found that this exchange strongly promoted children's thinking about the personalities of and relationships between characters in stories (Robertson and Good, 2003).

On the other hand, the lack of a specific narrative structure and learning direction may leave many participants floundering in the virtual environments without specific goals, "privileging confusion itself" and frustrating people's desire for having a story unfold as a result of their own meaningful choices (Murray, 1997; Stallabrass, 2003). As with the Internet, making information available is not enough to

[15] http://www.activeworlds.com/edu/ [last accessed: March 2006].

[16] http://secondlife.com/education [last accessed: March 2006].

qualify the setting as an educational experience. Additionally, the lack of high-quality multi-sensory representation in the physical sense (visual, auditory, and tactile) may support the case that these environments are incomplete learning environments in and of themselves. Moreover, students and teachers have to learn the necessary design and construction conventions to create specific text or model-based worlds and objects. The detailed mastery of these rules may in many cases be difficult and irrelevant to learning.

Similarly to the distance education field where the network is used to exchange information and material on learning related topics, networked VEs such as the aforementioned relate interactivity to communication and social interaction. Interacting, or communicating, with the virtual environment and through it with other humans, is an inherent feature of the medium, rather than a feature of the system that can be altered, engineered, and examined on its own for its effect on learning.

2.3.2.2 Classroom uses of virtual reality

Classroom uses of virtual reality are limited, primarily due to the high cost of VR systems. For this reason, the term "virtual reality" has been applied more widely to include desktop virtual reality (Winn, 1993). VR applications on the personal computer allow users to walk through simulated environments created via readily available commercial software, such as Virtus WalkThrough Pro[17] or VRML-based tools. Some slightly more expensive systems add peripheral devices, such as datagloves, joysticks, HMDs, or tracking, which plug directly into the desktop to provide a higher degree of interactivity.

Consequently, the VR projects developed using these low-end technologies are limited in size and complexity, and lack immersive and interactive qualities. Typical projects resemble 3D multimedia simulations and may involve the creation of simple models and minimalist worlds, which can be explored via "walkthroughs". Certain efforts develop interactivity a bit further, such as the Vertex project[18], which allows junior school children to explore simulated 3D virtual landscapes and architectures, and to interact and communicate with each other through avatars. However, in such projects, the interaction possibilities remain limited and are not designed to be central to the learning experience. In the classroom context, for example, a lot of the interaction takes place outside of these virtual environments, as in the case of Vertex which teachers used as an impetus to story-writing and other activities in the classroom. Perhaps the most significant use of desktop VR systems is in the education of learners with special needs or learning disabilities, who may not otherwise be able to experience certain aspects of the physical world or practice everyday life skill (Neale et al., 1999). In this case, other types of VR systems may be unusable due to health, safety, and ethical reasons (Cromby et al., 1995).

The integration of Internet and VRML software into the desktop configuration have expanded the usage of virtual reality in the classroom and added access to networked worlds, such as the ones described in the previous section. Research institutes such as The Virtual Reality and Education Laboratory at East Carolina University are also helping expand the use of VR at the level of the individual teachers by providing information about VR software for use in the classroom (Pantelidis, 1993). Although educators

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[17] Virtus WalkThrough Pro, http://www.virtus.com [last accessed: June 2006].

[18] Vertex, http://www.vertex.mdx.ac.uk [last accessed: December 2004].

may be willing to incorporate VR in their teaching practices, the introduction of VR in the classroom may bring with it multiple problems, including issues of funding, safety, teacher and student training, reshaping the curriculum, technological anxiety and confusion (Bricken, 1991). Any efforts rely on the individual action of the teachers, who may need to convince reluctant administrators, colleagues, and parents of the value of VR in their classroom.

2.3.2.3 Immersive virtual learning environments

In contrast to the desktop virtual learning environments described above, immersive virtual learning environments (VLEs), due to the use of high-end equipment and the dispersed non-standard methods of application development, are limited to situations with special funding, such as academic and research environments. Thus, many of the projects mentioned below were for the most part used with children only in structured experiment situations. Many of the early VR projects for children were developed especially for head-mounted display systems (HMDs) whilst the later projects started exploring the use of the physical space along with the virtual by employing projection-based or even mobile technologies.

A large part of this educational research has been focused on science education, as in the Newton-World and MaxwellWorld ScienceSpace projects developed by researchers at George Mason University and the University of Houston (Dede et al., 1996), which set out to explore the kinematics and dynamics of motion, electrostatic forces and other physics concepts. The initial formative evaluation reports on learners' engagement, surprise and understanding of the alternative representations of the concepts provided in the ScienceSpace worlds (Dede et al., 1996). Limitations and discomfort caused by the VR head-mounted displays hindered usability and learning. On the other hand, multisensory cues, multimodal interaction, and the introduction of multiple new representations is believed to have helped students develop correct mental models of the abstract material. However, other than navigation and pick-and-place activity, the worlds could not be dynamically altered through the learner's participation.

The Human Interface Technology Laboratory (HITL) at the University of Washington has been one of the early educational seedbeds for VR, with projects such as the Virtual Reality Roving Vehicle (VRRV) (Rose, 1995; Winn, 1993), Water on Tap (Byrne, 1996), and summer camp programmes in VR for students (Bricken and Byrne, 1993). The VRRV and summer camp projects focus on "world-building" activity, where students conceive and create the objects of their own virtual worlds, by using 3D modelling software on desktop computers. Although this sounds like a highly interactive process, it is focused only on the process involved in creating a virtual world rather than interacting with one. The actual immersive experience is limited to a short visit to the pre-designed virtual worlds (4 to 10-minute VR experiences). The concept that virtual reality is a process and not a product is important (Bricken, 1991), but does not take advantage of the potential educational benefits of the technology and does not justify its use.

One of the reasons students were not more actively involved with the actual virtual experience within the virtual reality system is the fact that the systems used by these projects (HMDs) were not designed to allow more than one participant at a time. The VRRV project attempts to overcome such restrictions in an interesting way, by travelling to schools and giving students (of grades 4-12) the possi-

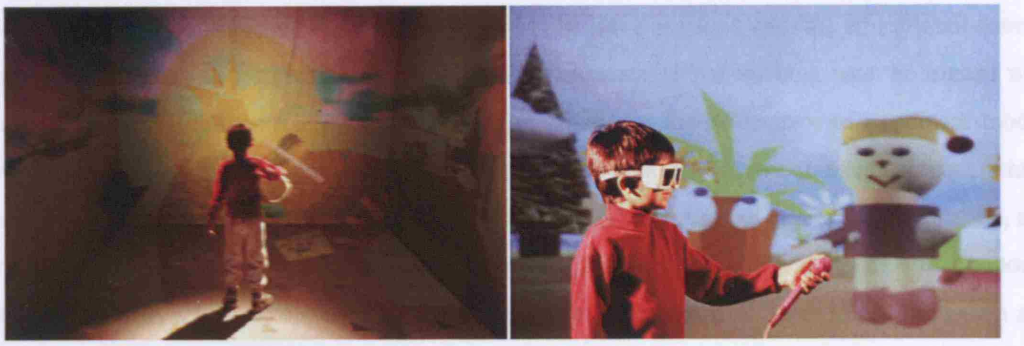

Figure 2.2: The NICE project: one of the early immersive virtual environments for young children in which multiple users could collaborate in planting a garden. Electronic Visualisation Laboratory, University of Illinois at Chicago, 1996-1997.

bility of experiencing VR, although still one at a time and for a short time. On the other hand, immersive projection-based VR displays, such as the CAVE (Cruz-Neira et al., 1993), the curved screen displays and the single-screen immersive desks, are freed from the limitations of HMDs (unwieldy hardware, single-user participation, short and infrequent immersive experiences), but not the limitations of size and cost. The more natural physical setup of the CAVE (a 10x10x10 ft. room rather than a device), the relatively non-intrusive interface hardware (no helmets to wear), and its multi-user support (more than one learner can share the experience at once) show promise as a VR tool for the development of learning environments. However, although these systems have been used successfully in the area of scientific visualization and industrial research and development, the development of CAVE applications for education has been limited, due primarily to practical limitations of cost and size.

CitySpace[19], a learning project where children built virtual cities, was demonstrated in the CAVE, but not in an educational context. This project, as with HITL's projects, emphasised the children's modelling activity prior to incorporating the models in a virtual city. Similarly, the CAVE was used as a medium to display the results of students' model building activity in the Virtual Solar System (VSS) project, an experimental undergraduate astronomy course in which students built models of the solar system in order to learn about astronomical phenomena (Barab et al., 1999).

The NICE (Narrative-based, Immersive, Constructionist/Collaborative Environments) project (Figure 2.2), an interactive virtual reality learning environment for young children, was one of the first educational VR applications designed and developed for a CAVE (Roussos et al., 1999). NICE served as a testbed for the exploration of virtual reality as a learning medium, focusing on informal education and domains with social content. As its acronym suggests, the NICE project embraced the constructivist approach to learning, combined with collaboration through telepresence, interactive "tools" that helped children to cultivate a virtual garden, and the development of a final narrative. In the study of childrens' behaviour in the NICE environment (Roussos, 1997), interactivity, identified with control over the environment, scored as the most significant motivational component of the learning experience. Giving one

[19]http://www.exploratorium.edu/MMP95/CitySpace.html [last accessed: April 2006].

child control meant that the child with control tended to be more engaged with the educational content resulting in a tendency to learn more. However, this "measurement" of learning must be treated with caution. In retrospect, the most serious shortcoming of NICE was the inadequacy of its science model. In an attempt to engage children, the interactive tools that were introduced were elements without natural analogs (umbrellas to indicate rainfall, sunglasses to indicate sunshine, facial expressions on plants), and naturally occurring features (e.g., the root systems of the garden plants) were represented in a cartoon-like fashion. These artefacts, deployed in a setting decontextualised from supporting discussion and instruction, may themselves have become the source of misconceptions regarding the underlying growth model that NICE was attempting to simulate. The balance among reality, abstraction, and engagement is particularly difficult to achieve and NICE likely veered sufficiently from reality to endanger the raison d'etre behind the project (Roussos et al., 1999).

Lessons learned from the NICE project helped in focusing and forming the design of the Round Earth Project (Moher et al., 1999) so that the learning domain was carefully selected to focus on a problem proved to be difficult with children. The Round Earth Project investigated how virtual reality could be used to help teach young children that the Earth is spherical when their everyday experiences tell them it is flat. The project carried out empirical work with pairs of students who collaborated using a distributed, immersive VR environment which allowed them to explore a small diameter asteroid. Each student used one of two distinct VR systems that were networked. The student who used the CAVE was the astronaut situated on the virtual asteroid surface with the ability to navigate using three buttons on a hand-held wand to move left, right, or forwards. The other student who was seated in front of a smaller VR system was the mission controller and was afforded a view of the asteroid from somewhere out in space, along with a direct video feed of the astronaut's view (Figure 2.3). VR was used as part of a larger strategy to create an alternative cognitive starting point where this concept could be established on its own before it was brought into contact with the learner's past experiences. However, the experimental studies proved that most children were unable to establish an "alternative cognitive starting point", as was required by the displacement learning model. The researchers believe that this was due to the revision of the bridging procedure that they made as a result of the various pilot studies, which introduced too many intermediate representations, thus creating cognitive demands that were simply too great for the subjects to handle. Further projects by the same group focused on investigating the effectiveness of virtual environments as simulated data collection environments for children engaged in inquiry-based science learning activities (Moher et al., 2001).

Finally, a few projects that were applied in informal educational settings are worth mentioning. Researchers at The Computer Museum developed an immersive VR application designed to teach children about the structure and function of cells in biology (Gay and Greschler, 1994). Their study set out to compare the immersive VR, a two-dimensional desktop program, and video instruction of cell biology. In the immersive VR application, the museum visitors were asked to construct cells from component parts, with successful completion indicated by an animation of internal cell function. In the other two conditions, visitors observed the computer or video program without the ability to interact. The subject

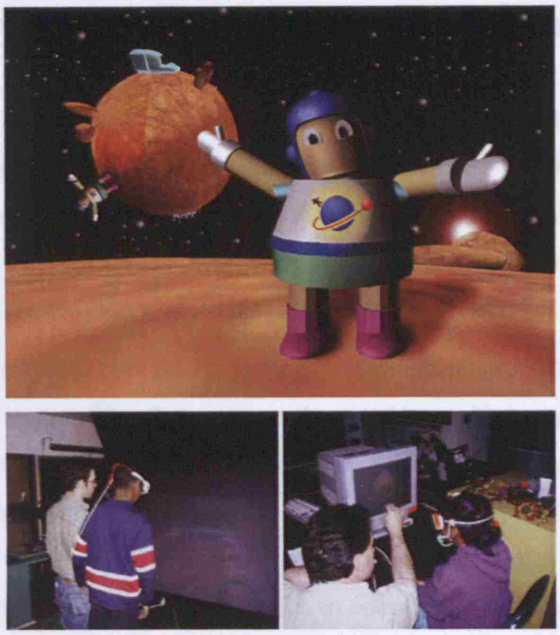

Figure 2.3: A view of the astronaut on the virtual asteroid developed by the Round Earth project to examine children's concepts and misconceptions regarding the shape of the earth (top). One child assumes the ground view of an astronaut in search of fuel cells (lower left). The other child has an overview of the asteroid from the position of mission control and must guide the astronaut on his quest (lower right). The Round Earth project. Electronic Visualisation Laboratory, University of Illinois at Chicago, 1998.

population was large and varied, consisting of randomly chosen museum visitors. In the comparison between immersive and non-immersive treatment groups, immersive subjects (children and adults) scored higher on the factual post-tests than the video users, demonstrating better retention of symbolic information (remembering the names and functions of the organelles), but lower than the 2D desktop users. The immersive users also enjoyed their experience the most and reported the most desire to continue learning about the topic after the experience (e.g., indicated more interest in taking a free biology class as a result of the experience).

Another exhibit-based research project, the Virtual Gorilla project (Allison et al., 1997) recreated the Gorilla Exhibit at Zoo Atlanta, allowing users to adopt the role of an adolescent gorilla, navigating the environment and observing other gorillas' reactions to their approach. Preliminary user testing through interviews with visitors and a small-scale evaluation within the context of a classroom elicited favorable responses in the sense of immersion, enjoyment, and successful communication of learning goals. In some cases, the ability to create mental associations that coupled spatial and symbolic information was observed, supporting the initial hypothesis that a VE that includes both spatial and abstract information allows learners to understand better the relationships between these two types of data. (Bowman et al., 1999).

More recently, since 2003, the British Broadcasting Corporation (BBC) has been exploring the use of Augmented Reality (AR) for learning. BBC's EducationAR research project has set out to evaluate the potential use of AR technologies in future broadcast production, learning, and online services for the classroom (Woolard, 2006). The early phases of the project concerning the relationship between the Earth, the Moon, and the Sun was evaluated with students 10-11 years old at the Science Museum of London and at the Westminster City Learning Centre. The evaluation aimed at assessing the pupil and teacher reaction to the new learning tool and evaluate impact on kinaesthetic learners. Preliminary findings reported that AR resulted in more movement on the part of the user, allowing inspection of AR objects in 3D rather than 2D, especially suited for kinaesthetic-based learners.

Despite the drive to empirically prove the value of VR for education, both quantitative and qualitative studies performed for most of the above projects have not been able to report much with respect to children's conceptual learning in the virtual environments, although some reported achievement of the learning goals they had initially set out to achieve. On the other hand, what most studies were able to consistently confirm was the high level of learner enjoyment, especially when compared to other media. This enhances the view that VR's largest contribution to education is its motivational strength, a view which does not depart from the same argument about the value of technology at large for education. The connection, however, that binds interactivity, engagement, and learning seems to be stronger; many of the ideas rooted in studies relating computers, motivation, and cognition (Malone and Lepper, 1987) can be directly related to the concept of interactivity and there are reasons to believe that interactivity may be a defining component in the successful outcome of a virtual learning environment.

2.3.3 Section summary

This section embarked on a review of educational technology environments for children, including microworlds, simulation environments, informal interactive learning spaces, and virtual reality learning projects, focussing on their methods of incorporating interactivity in their design or using it in their context.

Attention was drawn to the lack of systematic evaluation of the effect that interactivity in these environments may have on conceptual learning. Specifically, most of the developed educational virtual worlds that have undergone evaluation have done little to explore interactivity separately, even though some researchers (Salzman et al., 1999) have noted the need to investigate further the role of individual characteristics in determining the effectiveness of VR learning environments (but without being more specific on which characteristics should be investigated). Indicative of the fact that interactivity is considered to be an implicit feature of Virtual Reality that does not need to be studied may also be that the design of interactivity in educational VEs has been kept at a basic level, mostly using the default interactive operations provided by the technology, namely the ability to explore by navigation. The more advanced interactive virtual learning environments incorporated features that required the learner to make choices, sometimes using menu-driven multiple-choice interfaces. Hence, most of these cases have explored limited aspects of interactivity that perhaps may not have been the kind to actively involve the learner both physically and intellectually and, in turn, foster conceptual learning, at least in the constructivist sense.

2.4 Evaluating Virtual Environments and Virtual Learning Environments

As virtual environments become more commonplace in practical situations, training, and education, there is growing concern about judging their outcomes. As Dede et al. (1996) stated in the mid 90's, "one of the biggest stumbling blocks in VR research right now is the lack of concrete data on the usefulness of VR". This is especially true with regards to educational virtual environments, where relatively little principled empirical work has been carried out. Whitelock et al. (1996) have argued that effective evaluation methods need to be established to discover if conceptual learning takes place in VR.

A number of researchers have developed frameworks for structuring the evaluation of VEs (Gabbard et al., 1999; Hix et al., 1999; Bowman et al., 2002). However, most of these have been focused primarily on usability issues and usefulness for training and less on the efficacy of VEs for supporting learning in domains with high conceptual and social content. Gabbard et al. (1999), for example, propose a methodology for evaluating VE usability engineering, which involves sequentially performing user task analysis, expert guidelines-based evaluation, formative user-centered evaluation, and summative comparative evaluations. In this process both quantitative and qualitative data are acquired, where qualitative data are typically in the form of critical incidents that occur while a user performs task scenarios. A critical incident is usually a problem encountered by a user (such as an error, being unable to complete a task scenario, or user confusion) that noticeably affects task flow or task performance.

On the other hand, Marsh et al. (2001) argue that standard human-computer usability evaluation methods, such as usability inspection, do not address the vicarious nature of activities performed within a 3D virtual environment through either a first person perspective, i.e. the point-of-view of the person immersed in the VE, or a third person perspective, i.e. a point-of-view from behind, over the shoulder or viewed from a fixed position, or that of an object or person representing the user.

Similarly, Cobb et al. (2002b) note that the current immaturity of VEs in general and VLEs in particular has impacted on the types of evaluations that have been carried out. In their view, the most useful results found in virtual learning environment evaluations come from informal observed phenomena, not formal evaluations. They add, however, that it may be necessary for formal comparative studies to be carried out in order to show that the technology is educationally effective, an essential requirement if it is to be widely adopted in an educational setting. Researchers concerned specifically with the evaluation of virtual learning environments have considered it important to investigate the educational efficacy of the medium in specific learning situations or broader learning domains, and develop new rubrics of educational efficacy that compare it to other approaches (Roussos et al., 1999). Dede believes that the efficacy of VR can be truly established only by rigorously comparing VR's benefits to traditional educational methods and only "through careful analysis that can accurately diagnose the weaknesses and limitations of the technology" (Dede et al., 1996). He and his colleagues organised the evaluation of their science learning environments around four basic aspects: usability, learnability, usability vs. learnability and educational utility. Neale et al. (1999) have used Jonassen's constructivism principles (presented previously in Section 2.1.2) as a framework for evaluating VLEs for students with disabilities and special educational needs. In their case, up to 8-minutes of verbal observation data per interaction were structured into a multiple activity chart in which student behaviour supporting each principle was coded when it occurred. Other attempts (Rose, 1995; Salzman et al., 1999) at constructing methodologies and theoretical frameworks for evaluating learning activity within a VE have for the most part remained limited to particular applications and thus cannot be adopted to study specific aspects of the VR experience such as interactivity.

The question of whether VLEs require new and different evaluation methods beyond those in use by the HCI community or educational technology field, remains relatively unexplored. Many of the developed frameworks for evaluating learning follow a traditional approach, analogous to the standardised methods used to assess learning in formal educational contexts. This is not surprising as traditional educational assessment has proved to be remarkably resilient (Reeves and Okey, 1996), despite growing criticism of its effectiveness in capturing what really goes on in the learning process. However, the introduction of constructivist and situative perspectives of learning in educational practice has intensified the need to develop "authentic" evaluation techniques that are directly related to the learning approaches themselves. Hence, the increasing interest in alternative forms of evaluation is reflected in the proliferation of terms, such as authentic assessment[20], performance assessment, and portfolio assessment (Reeves and Okey, 1996), that focus primarily on the process rather than just the product of learning. These methods may, in many cases, involve learners in the evaluation of their own learning, emphasising common themes, such as problem solving and complex learning, which entail a wide range of responses and challenging tasks with multiple steps, time, and effort. Alternative assessment also affords the ability to include motivation as an important factor in the evaluation process. This is especially relevant to virtual learning environments which rely heavily on their motivational impact. The critics of alternative assessment, on the other hand, complain that it is time and labour intensive, and heterogeneous, as the outcome of the evaluation can vary widely in the specific knowledge domain being judged. It can also vary widely because individual students' performance varies. It relies on students' verbal and communication abilities and there is no easy comparison among students. Perhaps the most common critique states that alternative forms of evaluation can not be generalised to other contexts. However, cognitive psychologists as well as the education field, do not consider this a disadvantage, as they believe that the nature of knowledge itself is highly contextualised with limited generalisability (Brown et al., 1989).

Virtual learning environments are dynamic, contextually rich environments with a multitude of components that influence activity within them. Thus, alternative evaluation methodologies are considered more pertinent in capturing the dynamics among all these components. In the next chapter, such a theoretical methodology, which can provide the necessary structure to describe and analyse the dynamic and contextual activity that takes place in immersive virtual environments, will be developed.

[20]The word 'assessment' is used here in the broader sense of the U.S. terminology, as opposed to the UK context in which 'assessment' typically means curriculum testing.

2.5 Summary

The purpose of this chapter has been to identify the claims, common assumptions, and results from investigations made with regards to the effect of interactivity on learning; to review the work that is carried out in the several interrelated areas that form the background of this research; and finally to situate this thesis within each of these areas.

A review of the literature on learning indicated that the notion of what constitutes learning has evolved throughout the years from a behaviouristic to a constructivist and social constructivist approach. This evolution and the general trends were described and the constructivist tradition was adopted as the theoretical model of learning for this work. As with the theories on learning, the many explanations of what interactivity is were reviewed according to their context. A "working" definition of interactivity as a hierarchical "call and response" process involving multiple decisions and components on both a physical and an intellectual level has been adopted. Specifically for VR, the framework of Pares and Pares (2001) is used, according to which three levels of activity characterise a virtual environment: exploration of the VE as the basic level of activity, manipulation of the VE or of its parameters as a core level of interactivity with the system, and the ability to alter the system of operation itself (the contributive level) as the highest level of interactivity. The impact of these different levels of interactivity on learning will be explored later in this thesis.

This review found that a large volume of work (especially in the area of distance education) identifies interactivity as a beneficial component for learning. However, a non-critical position toward interactivity is assumed. Very few studies question the significance of interactivity as a facilitator of the learning process. Even fewer go further to consider which forms of interactivity, if any, are effective. Interactive learning environments were reviewed from a number of different contexts, focusing on learning environments that use 3D graphic representations and VR as their main display medium. The informal education context has seen a few such projects/productions, most of which have been developed with a focus on "edutainment". As noted, this research on interactivity involves great interest in these types of situated environments and the potential learning impact they may have on the large numbers of young visitors they attract. However, as this review reveals, very few of these projects have carried out any research on their actual impact, and where such studies exist, these are mostly focused on technical descriptions of the systems and usability rather than on studying any effects of the environments on learning. Furthermore, due to the non-academic and somewhat commercial nature of the area, much research remains unpublished and unavailable to other researchers or practitioners.

The educational VR research projects, on the other hand, have mostly been developed in academic laboratories in order to apply and test the potential of virtual reality as a medium for educating students. In some projects, very specific applications of VR have been developed (i.e. in chemistry, physics, etc) that examine how students react to these and if they achieve the learning goal. Comparisons made with other, more conventional media, produced limited or questionable results due to the fact that the complex nature of the medium was not taken into account and the evaluations isolated parameters with the danger of neglecting important contextual information. In other cases, the opposite holds, with exploratory studies that looked at general aspects rather than specific attributes of the VEs and their effect on learning, resulting in little more than observations on the motivational value and overall promise of VR for education. In any case, as with the VR projects in the museums, these educational VR studies have either not provided the analytical evidence to demonstrate learning or, where an educational impact was perceived, there is no explanation of why. But more importantly, the role of interactivity within learning has not been the focus of any of the evaluations carried out. The review of various methodologies and frameworks used to evaluate VEs showed that none of the existing frameworks have been designed to capture the contextual, activity-based, and dynamically evolving nature of a virtual learning environment and of human behaviour with it or within it.

Given the above, this review has identified deficiencies in the study of VR environments for learning. Furthermore, the lack of studies that explore interactivity, the lack of understanding of its role in VR-based learning, and the lack of pertinent methodological frameworks for evaluation, leave a gap in the development of virtual reality research that calls for further examination. The research questions that have emerged ask if and how interactivity in a virtual learning environment can influence learning. To answer these questions, the first issue to be addressed is how they will be studied: in other words, which methodology will be deployed or constructed to provide evidence that interactivity in a virtual environment influences learning. In the next chapter, the methodological issues and frameworks considered and adopted by this research are presented.

Chapter 3

Methodology

To be able to study the effect of interactivity on conceptual learning down to the level of detail of the separate interaction elements that are afforded by a virtual environment, it was considered necessary to explore the research problem through a set of empirical studies. Therefore, the research presented in this thesis includes an exploratory study, described in Chapter 4, and a main study, described in Chapter 6, investigating the effect of interactivity on conceptual learning. This chapter develops the common rationale behind the design of these studies, and describes the specific techniques, methods and procedures that were adopted. The chapter is divided into two sections: Section 3.1, which describes the methodology used for collecting data, and Section 3.2, which introduces the methodology for data analysis.

As noted in the previous chapter, in Section 2.4, researchers in the area of VR and education would argue that using just paper and pencil, in the form of standardised tests, is not an appropriate way to evaluate the effectiveness of an interactive virtual learning experience. Winn (1993) illustrated this view by arguing that "...instructional designers are wrong to assume that they can base instructional strategies on the analysis of an objective, standard world...". He believed that the evaluation of learning "can only tell us what students appear, or pretend to know..., not what they really know." As VR can be a dynamic learning tool, evaluation should be inextricably coupled with the actual learning activity. In essence, what applies to the evaluation of constructivist learning environments should also apply to the evaluation of virtual learning environments, as they both place learners in positions where they can explore, experiment, and actively solve problems. Considering the dynamic nature and idiosyncrasies of the VR medium, the complexity and social context of the topic of this research (learning, interactivity), and the fact that the research target group is young children, the key to conducting meaningful assessment will be to apply multiple measures of learning and performance (Rose, 1995), both quantitative and qualitative.

Therefore, the approach taken by this research has been to meld techniques and methods that have been considered relevant and appropriate for both the collection of data and the analysis. This methodology combines quantitative and qualitative approaches. The main reason given for the formulation of this integrated approach is that it opens up the possibility of combining the positive elements of both quantitative and qualitative methods, resulting in a variety of evidence and a more holistic explanation of the research problem.

Quantitative and qualitative research methods have been viewed as manifestations of two contrary research paradigms (Lincoln and Guba, 1986), thus the choice between a quantitative or a qualitative research methodology has been a key tension in the field of human-computer interaction. Qualitative research methods seem more suited for studying learning, especially in rich contexts where constructivist and social constructivist views of learning are supported and where researchers can construct their knowledge about the topic at hand by studying emergent data. An issue of concern, however, with observation-based qualitative research is how theoretical and interpretational bias should be addressed. Science demands observations that are replicable and amenable to scientific analysis, while still faithful to the dynamics of the phenomenon studied (Bakeman and Gottman, 1997). A way around this problem has been to eliminate biases through the rigorous standardisation of qualitative methods and procedures (e.g., by using coding and validation procedures such as constant comparative analysis, where elements and emergent categories are constantly sifted and compared throughout the course of the analysis, or carrying out independent analysis of the data by more than one researcher and respondent validation, where interim research findings are cross-checked with respondents). On the other hand, an issue of concern with quantitative and statistical research is that it cannot account for the richness of human behaviour (Lincoln and Guba, 1986).

Schofield and Anderson (1987) note that qualitative and quantitative methods "are not rooted in opposite and irreconcilable paradigms", citing Thomas Kuhn's views that no single paradigm, whether quantitative or qualitative, can answer all the problems within its domain. Adopting this view, a combination of methods for data collection and analysis was considered appropriate to examine the given question about the interplay of learning goals and activity in immersive environments. The process of methodological "triangulation", i.e by using more than one method of data collection and empirical materials to answer a research question, is seen as being the successful merging of the two methodologies to overcome the weakness or intrinsic biases that may be present in single method research and increase the credibility and validity of the result. In this process, qualitative and quantitative methodologies offer complementary rather than competing perspectives that are used to reinforce each other's findings rather than being "antagonistic" to each other (Schofield and Anderson, 1987).

In other words, the key points of this combined methodology that enmeshes data collection and analysis are:

- the use of more than one method of data collection, combining observation of activity transcripts, questionnaires, interviews, and log files, all of which can offer complementary perspectives to the examination of the research question

- a research methodology that is rooted in a synthesis of quantitative and qualitative measures, which, in combination, can point to correlationships in the analysis of the data

The following sections describe this combined methodology. Specifically, Section 3.1 covers the methodological approach for data collection and Section 3.2 the methods for data analysis.

3.1 Methodological Approach for Data Collection

This section outlines the data collection methods used by this research, as well as the selection of participants, apparatus, and procedure used for the experiments. As Chi (1997) argues, the analysis of data is only as good as the way the data was collected. In order to ensure validity and reliability of the collected data (Cohen et al., 2000, p.305), the methods used in the studies allowed for multiple ways of gathering information. These methods are described in the following section.

3.1.1 Evaluation methods

This research combines an experimental and an ethnographical approach. Therefore, several different instruments for collecting data have been considered and are described below, along with their advantages and shortcomings. These include demographics, pre- and post- questionnaires, direct observation, interviews and log files. All of these methods were used for the main study, described in Chapter 6, whilst for the exploratory study, presented in Chapter 4, it was direct observation that was mainly used. In both studies, the particular idiosyncrasies of working with children were taken into account (such as their varied ability to verbalise and limited attention spans) and, as a result, the most appropriate methods were formulated.

3.1.1.1 Ethical issues

Working with human participants requires acquiring their consent. In the case of carrying out experiments that involve minors, ethical considerations are even more prevalent.

For this research, a full application for ethical and Data Protection approval were submitted to the University College London's Committee on the Ethics of non-NHS Human Research a few months before the studies begun. The examination of the application involves looking at a range of issues, from possible risks and health issues to such issues as the quality of the letter to parents and children and the suitability of the methodology for children.

In accordance with the ethics requirements, a cover letter explaining the research, procedure, and any risks and discomforts was given to participants' parents prior to the study. An informed consent form was also given to parents, but only for the main study (including the pilot phase). The form explicitly asked for written consent to being audio and videotaped. Participants' parents were informed that all data, including audiovisual records, would be confidential and would only be used for the purpose of data analysis. In some cases where photographs or videos have been used for other purposes, such as conference presentations and research publications, additional informal permission was obtained from the parents, even if this had been given already in the original consent. Parents were also informed that their child would be free to withdraw from the experiment at any time and without giving a reason for withdrawing. This information was also communicated verbally to the parents by the researcher.

Other than their name, age, and the name of their school, parents and children were not asked to provide information that would identify their ethnicity, religion or socioeconomic situation. All required steps were taken to preserve the confidentiality of the information acquired and to prevent the identity of participants in the research being revealed without their expressed permission. Hence, throughout this thesis, where children are referred to by first names these are pseudonyms.

Conducting experiments with human subjects usually requires that the subjects are paid for their participation in the studies. As participants in these studies were children, payment or incentives in monetary form were considered inappropriate. Instead, a gift pack was prepared and given to each child as a surprise at the end of the study (Appendix C.7). Additionally, reimbursement for transportation costs to/from the study site was foreseen for the parents who brought their children.

The cover letter and forms given to the parents can be found in Appendix C, while details concerning the process of obtaining approval for the studies can be found in Appendix E.

3.1.1.2 User profiling or demographics questionnaire

It is common in empirical research to collect demographic information of the user population taking part in a study, in order to extract general information about the sample and its representativeness. Furthermore, in qualitative research it is useful to create a profile for each participant, especially if conducting a case-based analysis. For this research, the user profiling questionnaire was intended to capture base-line demographic information (gender, age, year in school) about participants and participant experience with computers, computer game play, and virtual reality. This information was used for the main study, described in Chapter 6. Further information on the user profiling questionnaire can be found in Appendix C.2.

3.1.1.3 Pre-test

As is typical of pre-tests, questions are designed to identify participants' existing knowledge of the topic studied, prior to entering the study. As this study involved young participants, care had to be taken to design questionnaires that were understandable by them.

Researchers and practitioners (Read, 2005) that have worked with children note that children aged 8 to 12 are able to complete questionnaires provided that the language used is simple. For example, children tend to be very literal and cannot easily understand negatively constructed questions, therefore interspersing positive and negative statements when determining attitudes is not advisable (whereas practice with adults favours the opposite). Read (2005) notes that children with more developed language skills produce better data, as research has indicated that low reading ability correlates with the number of unanswered questions. Other reasons for questions being unanswered include short concentration spans or boredom. She has found that boys are more likely to leave questions unanswered than girls and that the proportion of unanswered questions decreases with age. Therefore, the language that is used in the questionnaires, whether written or verbal, needs to be the language used by the children and to have meaning even for the least articulate members of the group (Read, 2005). Practical ways of ensuring that this is the case include carrying out a pilot study, asking teachers, or researching age related language development, all of which were carried out in order to construct the questionnaires used for this research.

For this research, a written pre-test questionnaire was designed for the main study (Chapter 6 and Appendix C.3) while the exploratory study (Chapter 4) used a less formal verbal process for identifying participants' prior knowledge of the learning domain.

3.1.1.4 Direct observation

Direct, in situ, observation has been the primary method of data collection for the studies of this research. A think-aloud technique was encouraged in order to facilitate observation and analysis (Ericsson and Simon, 1993). Each participant was asked to concurrently verbalise her actions and thoughts whilst interacting in the virtual environment. However, there are issues with the think-aloud protocol that have been noted by researchers who have been working with children: children have different capacity to verbalise, they have different levels of extroversion where some are more verbose than others, their knowledge and skills may be different, and although generally being very honest in their judgements, the reliability of reported data is questionable (Druin, 1999; Hanna et al., 1999; Baauw and Markopoulos, 2004; Markopoulos and Bekker, 2003).

The role of the observer is another point to be noted. Chi (1997) notes that the observer must be as unobtrusive or as uniformly intrusive as possible, while at the same time ensuring that the participants are occasionally reminded to think-aloud (Nielsen et al., 2002). There is always the risk of the observer intervening too much to help the participant, possibly altering the result. Ericsson and Simon (1993) have also raised the concern that the act of verbalising changes the cognitive processes. The extra mental workload required for verbalising and the uncomfortable social situation of having a quiet observer telling you to 'keep talking' make it a hard method to apply, particularly for children users. Older children, aged 9-12, are more able to provide a running commentary during interaction and think aloud helps identify more usability problems than a post-task interview or a post-task questionnaire (Markopoulos and Bekker, 2003). There has not been a similar study with younger children. A variation that has shown promise could be what has been called 'Active Intervention', where the evaluator prompts the children for explanations of what they are doing and to give a commentary on their interaction. Usability evaluation sessions with children carried out by van Kesteren et al. (2003) have shown that most verbal comments were gathered during Active Intervention sessions versus other methods such as the think aloud or co-discovery, and that quiet children are better able to provide verbal comments when a more active way of prompting is applied, for example by asking questions. Hence, for these studies, it was decided that the observer would assume the more active role of a "cultural informant" rather than that of a "detector" who passively records what is "there" (Bakeman and Gottman, 1997).

Finally, the tools used to support observation included a video camera for recording all of the sessions and interviews, with an external microphone for capturing audio of sufficiently good quality for later transcription (Figure 3.3).

3.1.1.5 Informal conversational and semi-structured interviews

Given that the participants in these studies were young children, a combination of informal conversational and semi-structured interviews was chosen. Informal conversational, or unstructured, interviews are typically conducted in qualitative studies and allow the interviewer to ask the participant questions that emerge from the course of the discussion (Diamond, 1999). Since questions emerge from the immediate context there is no predetermination of question topics or wording (Cohen et al., 2000). The advantage of this informal kind of interviewing is that it increases the salience and relevance of questions;

interviews are built on and emerge from observations and can consequently be matched to individuals and circumstances (Cohen et al., 2000). Another advantage of informal conversational interviews is their less threatening nature in comparison to more formal interviews (Diamond, 1999), an important advantage when working with children. The weakness is that different information is collected from different people with different questions, which can make data organisation and analysis difficult.

Therefore, a more structured approach may be best followed in cases where questions do not arise 'naturally'. In the case of a semi-structured interview, a set of research questions is specified in advance in outline form. This gives the interviewer a fair degree of flexibility in the way that the interview is done since the interviewer can decide the sequence and working of questions in the course of the interview. This kind of flexibility is ideally suited to explorative research where little is known about the research problem in advance. It is also particulary useful when interviewing children, as roughly the same topics need to be covered, but the questions may need to be asked in different ways depending on the child's level of understanding (Diamond, 1999). Finally, the outline increases the comprehensiveness of the data and makes data collection more systematic for each respondent; yet, interviews remain conversational and situational (Cohen et al., 2000).

For this research, conversational and semi-structured interviews were carried out by the researcher directly after the experience, starting out with questions about participants' satisfaction and engagement. Conversational interviews were used in the first study since it was purely exploratory (Chapter 4), moving to the more structured form of interview for the main study (Chapter 6). The continuation of the interview by revisiting activity based on responses to the post-test was also considered and pursued where possible in this research. Chi (1997) calls this type of approach a "complement approach" and considers it the most straightforward way to integrate quantitative measures along with the qualitative measures. This approach has been used widely, for example when collecting scores of the problem-solving along with the verbalisations of problem solving. In this case, the quantitative data collected can serve as confirmation of the qualitative analyses and vice versa.

3.1.1.6 Post-test

Post-tests are carried out after treatments in order to examine if the study had any effect on participants. For this research, a post-test was designed as part of the main study. Similarly to the pre-test, the post-test was kept short, taking into account that participants were children and would have to complete the task after a potentially lengthy and exciting experience. More information on the post-test and its use for the main study can be found in Appendix C.5.

3.1.1.7 Transcription

The transcription of speech recorded on video to written text is a crucial step in the data collection and data analysis process, since it is the transcribed material on which the analysis or any future analyses will be based. Transcriptions also allow for the researcher or other researchers to easily review the observation sessions later, in replication or independent analyses of the data (Patton, 1987). Nevertheless, the shortcomings of transcriptions have been noted by researchers (Cohen et al., 2000) who point out that the loss of data from the original encounter is inevitable, for a transcription represents the translation from one set of rule systems (oral and non-verbal) to another very remote rule system (written language).

Since all transcripts in this research derived from videotaped material, it was possible to comment on the non-verbal communication that was taking place in addition to the oral exchange. This way facial and bodily expression and activity could be noted in conjunction to spoken words, and long and short pauses, if considered important to the section that was being transcribed. The use of a transcription tool described in Appendix D aided this process.

3.1.1.8 Log files

Computer-recorded log files can be useful in recording time and other quantifiable information that concern the session. For this research, computer log files were used to record each participant's interaction within the interactive VE that was designed for the main study (Chapters 5 and 6). Certain information from the log files were then incorporated into the transcribed observations to create a combined record of each session. An example of a log file generated by this research can be found in Appendix C.6.

3.1.2 Selection of participants

Children between 7 and 12 years old were recruited to participate in the various phases of this research. The reason for working with children in this age group is based on Piaget's classification of the human's developmental stages. In Piaget's *concrete operations* stage children can classify things and can think logically. It is this stage when abstract thinking and mental models start to form. However, since age is not always indicative of aptitude, this age range was chosen mostly as a starting point and further questions were asked during the recruitment process in order to identify whether each participant fit the specific criteria placed by each study.

A total of 60 children participated in the experiments and pilot studies of this research; 3 participants took part in the exploratory study, 7 participants took part in the piloting stage of the main study (excluding 10 adults that participated in the usability testing of the VE) and a total of 50 participants took part in the main study (17 in an interactive virtual reality condition, 14 in a passive virtual reality condition, and 19 in the non-VR condition).

Recruiting was carried out in different ways, depending on the study. For the exploratory and pilot studies, the recruitment process was less formal. For the main study a more structured recruiting process was followed including posters, and contacting schools, museums, and organisations with constant access to children (such as the BBC and its Classroom of the Future programme, the NESTA Future lab, the BETT Educational Technology fair and others). Chapter 6 and Appendix C.8 contain more information on the recruitment material and process.

Figure 3.1: The hand-held wireless wand used for interaction in the virtual environment.

3.1.3 Apparatus

For the virtual reality part of the experiments, the system used for testing was a CAVE-like display[1]. The CAVE is a room-sized virtual reality system constructed of three translucent walls and a floor, onto which high-resolution computer-generated stereoscopic images are projected (Cruz-Neira et al., 1993).

The user dons a pair of active stereo glasses to experience the virtual world stereoscopically. A tracked position and orientation interaction device with a joystick and buttons is used by the user to interact with the virtual world that is displayed onto the projection walls and floor. Specifically, the input device used in the CAVE for these studies is a wireless Intersense^{TM} wand with a joystick and 4 coloured buttons (Figure 3.1). In both studies, the interaction device was used to complete the virtual tasks assigned.

The user's head position and orientation in the CAVE is also tracked by a sensor, which is typically placed on the top edge of the stereo glasses. Due to the size of the glasses (which, unfortunately, are not designed for heads of different sizes, let alone children's heads) and the fact that the weight of the head tracker on the glasses placed an extra burden on each child's head, a more comfortable solution had to be devised. The head tracker was fastened (using VELCRO^{TM} strips) on a baseball cap, which was then worn reversed so that the tracker cable would fall behind the participant's head (Figure 3.2).

All sessions, in all studies, were videotaped. The camera was pointed toward the front wall of the CAVE, capturing each participant's back, the front screen, the floor and part of the side walls (Figure 3.3). An external microphone connected to the video camera by a long cable was used to increase audio quality. The user wore the microphone as a clip-on. In total, the user had to wear the stereoglasses, the tracked baseball cap and the microphone, and, in the case of the interactive VR sessions, hold the interaction device.

[1] The CAVE (CAVE Automatic Virtual Environment) is a Registered Trademark of the Board of Trustees of the University of Illinois, originally designed by the Electronic Visualization Laboratory of the University of Illinois at Chicago and presented in (Cruz-Neira et al., 1993). The VR display actually used for these experiments is a ReaCTor^{TM}. However, for the purpose of brevity and simplicity, the word CAVE will be used throughout this document to indicate the generic cubic immersive display system of this type.

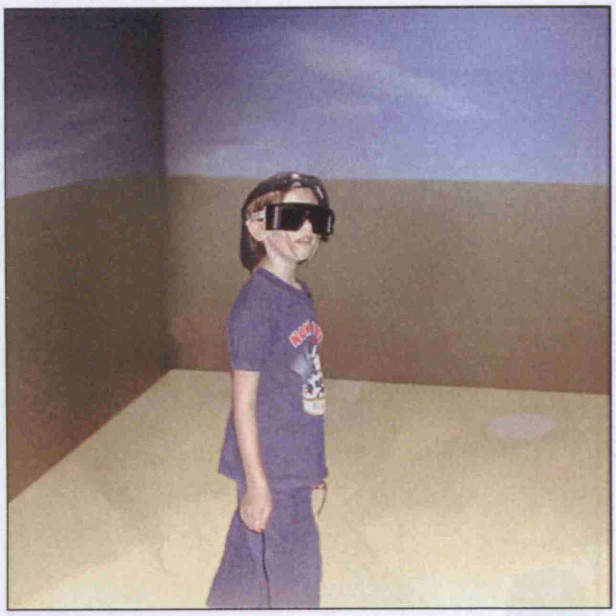

Figure 3.2: A pair of active stereo glasses and a cap with the head tracker was worn by each participant in the virtual reality room.

Briefing, de-briefing, and questions took place in a separate room and inside the activity room. In some cases, the interviews took place in the virtual reality CAVE with the room lights on. The participants were also trained on the use of the system with the use of the same devices and apparatus. For the main study, a special virtual training environment was created and used to train participants in navigation and object selection (described in Appendix B.1).

Other equipment and material particular to each study of this research (e.g., a LEGO environment used for the non-VR condition of the main study) are described in their relevant sections.

3.1.4 Procedure

Both the exploratory and the main study relied primarily on the use of the CAVE virtual reality system, which is located at the University College London's Department of Computer Science building in central London. Therefore, there were aspects of procedure that were common to both these studies.

As all the VR studies took place on weekends when the University restricts access to the building to staff only, the researcher had to greet participants and their parents at either the entrance of a nearby landmark bookstore or at the nearest metro station, and lead them to the study area (see Appendix C for the map and communication material provided to parents). Upon arrival to the study area, participants were seated on comfortable chairs. The researcher (who was sometimes aided by colleagues) would then go through some practical information about the building and the study, and encourage the participants to feel comfortable, offering juice and a selection of cookies and muffins. The advantage of carrying out the studies on weekends was that the virtual reality equipment -usually in high demand- was completely available and all areas of the study were free from other people who could have made the participants feel uncomfortable. The disadvantages for the researcher were that no technical support was available on

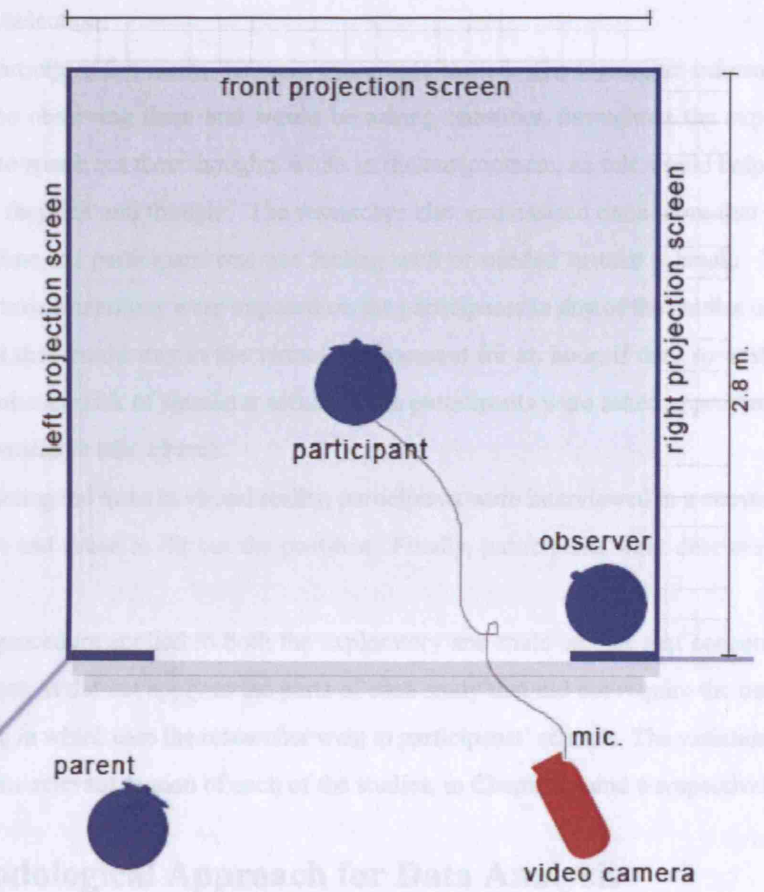

Figure 3.3: The immersive VR experimental setup used for this research, depicting the positions of individuals and equipment that took part in the studies.

weekends, and that a maximum of six participants could be booked on any given weekend, thus delaying considerably the completion of the studies (it, indeed, took several months to complete the VR studies).

An introduction to the study was given first to each participant and then to the accompanying parents or guardians. Participants were told that their role was very important, as they would be helping the researcher understand and ultimately design better educational virtual reality programmes for kids. They were then given the profiling and pre-test questionnaires to complete, if required by the study. Parents were given a printed version of the information sheet that had already been sent to them by e-mail. The sheet detailed the study procedures and the possible risks associated with using virtual reality equipment (see Appendix C). They were then asked to sign the informed consent form, in accordance with the procedures required by the ethics committee (see Appendix E). Many of the parents had already signed and brought with them the form that had been sent to them by e-mail.

After the the forms and questionnaires had been completed, the participant was led to the virtual room where the main experience would take place. Parents were given the chance to observe their child's experience, if the child agreed. The virtual reality technology was explained to participants and the various devices (head tracker, stereoglasses, microphone) were fitted onto the participant. Participants then went through training in the immersive environment, which included navigation, if applicable to the study, and object selection.

When the participant felt ready, the main experience started. The researcher informed participants that she would be observing them and would be asking questions throughout the experience. They were also asked to speak out their thoughts while in the environment, as this would help the researcher understand what they felt and thought. The researcher also emphasised once more that the experience could stop any time the participant was not feeling well or needed to take a break. This was quite important, as no time limitations were imposed on the participants in any of the studies of this research, which meant that they could stay in the virtual environment for an hour, if they so wished. However, in order to minimise the risk of simulator sickness, the participants were asked approximately every 10 minutes if they wanted to take a break.

After completing the tasks in virtual reality, participants were interviewed in a conversational semi-structured format and asked to fill out the post-test. Finally, participants were debriefed and received their gifts.

The above procedure applied to both the exploratory and main studies that concerned the virtual reality environment. It did not apply to the parts of each study that did not require the use of the virtual reality equipment, in which case the researcher went to participants' schools. The variations in procedure are described in the relevant section of each of the studies, in Chapters 4 and 6 respectively.

3.2 Methodological Approach for Data Analysis

This section presents the methods used to analyse the data collected for the studies. The data collected for each participant in the main study (Chapter 6) included observational data recorded on video, responses to a demographics questionnaire, a pre-test, a post-test, and a semi-structured interview, and the computer generated log file. The first section, Section 3.2.1, covers the statistical methods used to analyse the pre- and post-tests of the main experiment. Sections 3.2.2, 3.2.3, and 3.2.4 present the qualitative methodology that was adopted and used for all studies.

3.2.1 Quantitative analysis

Quantitative analysis was performed only on the pre- and post-test scores of the main study (Section 7.2). A set of n ($n=11$) questions were included in each of the pre- and post-test questionnaires. The questionnaires were designed to produce only dichotomous (binomial) 'true' or 'false' responses, i.e. a correct or an incorrect response to each question. The questions that, for whatever reason, were not answered (i.e. questions that were not attempted by the participants) were considered to be false, hence the response had always one of two outcomes. The null hypothesis formulated for the main study was that participants' responses are 'random'.

The choice of the statistical model for the quantitative analysis was determined by the outcome variable. The outcome variable is the count of correct answers out of the total number of questions. Since, in this case, each response is dichotomous and the outcome variable is the sum of dichotomous variables, logistic regression was used as the model that better fit the data for the analysis. Logistic regression is a standard method of statistical analysis which is best suited for data with a binomial distribution (McCullagh and Nelder, 1989). It is used to model the relationship between a dichotomous response variable and a set of explanatory variables that can be dichotomous (e.g., true or false, yes or no, success or failure, 1 or 0), nominal / categorical (e.g., gender) or continuous (e.g., age). Logistic regression provides a technique of nonlinear modeling for multivariate binary data, which is analogous to multiple regression and ANOVA for continuous responses. In this case, analysis of deviance tables are constructed, which are analogous to analysis of variance tables. The deviance is the "goodness of fit" measure for a logistic regression model -it can be likened to the residual sum of squares in a linear regression model. The smaller the deviance the better the fit of the logistic model. A large value for the deviance is an indication that there is a significant lack of fit for the logistic model in that insufficient or inappropriate variables may have been included. For example, student scores may have been influenced by how tired they were, but such data may not be available: if it were available, the fit of the model might have been improved. The deviance has a chi-squared (χ^2) distribution. This means that a χ^2 value represents the change in deviance if the corresponding variable were eliminated from the model. The degrees of freedom is determined by the number of observations less the number of parameters estimated. Therefore, to perform tests of hypotheses regarding the fit of the model, the deviance is compared to the percentiles of a χ^2 distribution. This kind of statistical modeling was carried out with GLIM[2].

Independent, dependent and explanatory variables were defined for the main study of this research. The independent variable was the condition (a total of three conditions were designed for the main study, see Section 6.1.1). The dependent or response variable included the participants' scores from the post-tests. All other variables, such as gender, age or year in school, frequency of computer usage and game playing, were the explanatory variables. The number of correct responses were counted out of all responses and the response variable was related to linear combinations of the independent (i.e., condition) and explanatory (all the other) variables.

Finally, descriptive statistics were used in the main study to form a picture of the sample, including means and standard deviations for the participants' age, gender, aptitude, and experience with computers and virtual reality (Section 7.1).

3.2.2 Qualitative analysis

In the literature review (Chapter 2), it was argued that a constructivist approach to learning would be appropriate for studying interactivity in a VE and learning.

However, no established methodology has been found that uses this theoretical grounding to study VR environments for learning. Only one study by Barab et al. (Barab et al., 1999) with a strong social constructivist dimension has been identified, which adopts Activity Theory as a method for analysing a series of design experiments on a VR-based astronomy course. This study used a naturalistic grounded approach based on both quantitative and qualitative data that were collected through direct observation, field notes, interviews, document and artefact analysis, and retrospective recall analysis. The collected data captured discussions between students and teachers, documented practices, resources and progress,

[2]Generalised Linear Interactive Modelling (GLIM) package, http://www.nag.co.uk/stats/gdge/gdge_publications.asp [last accessed: June 2006].

and supported and refuted emerging hypotheses about how these practices and resources evolved over time. The data was then grouped into units of analysis called "nodes" and large databases containing these nodes of information were formed.

A similar methodology has been chosen for this research. However, in this research, no prejudgement of what counts as conceptual understanding was made at the outset, thus the same descriptive framework of dividing chunks of data into nodes and grouping nodes into databases could not be used. Instead participants' interactions within the VE were interpreted by examining instances of activity that were thought to provide evidence of change in understanding. Like the study of Barab et al., this represents a grounded approach in that it documents practices and supports and refutes emerging hypotheses. Unlike that study, however, this research is not naturalistic since it was time-constrained and involved an environment specifically designed to allow the examination of a certain parameter, that of interactivity.

Based both on observation and on the verbal communication with the participants during and after the sessions, but also on the researcher's conceptions of the type of learning that was sought (as defined in section 2.1.1), a repertoire of the kinds of learning that could or did take place was formed. This repertoire includes the following different kinds of learning, which were sought for in the analysis of the data:

- Conceptual change, where participants revise their conceptions or change their interpretation of something, as evidenced through conversations of the type: "Why have you done this?", "Because I realised that there are now two different types of column instead of one...", and so on. When a participant says something and then provides a revised explanation later on, this may be an indication of conceptual change.

- Additive knowledge, where participants have added to what they have already experienced. One could argue that this is the basis of constructivist learning, as long as this process of additive knowledge involves some kind of reinterpretation of what was done before rather than just the accumulation of information. Additive knowledge may be identified through a discursive process with the user, indicated by comments such as, "Oh I didn't realise that before". When a participant says something during one task and then extends or develops this in the next task, that might be an indication of adding to previous knowledge.

- Changes in behaviour. Even though a change in behaviour may not signify constructivist learning, since participants may change their behaviour and not understand why or may become better in something or succeed in a task and not actually understand it, it must still be recognised that this is a form of learning (at least, according to the behaviourists, as noted in section 2.1.1). Such changes in behaviour may be an important indication of learning in this study because all one may be able to infer with confidence from the observational data may be that behaviour has changed, rather than having evidence of some change in understanding. Changes in behaviour are mostly identified through observation rather than through what the participants say. If the participants try to do something, fail and then try to do it again later on, an effort would be made to identify if they did it in a different way. This would be an indication of behavioural change.

The above three categories constitute a general definition of learning for the purpose of analysing the study data. During the qualitative analysis, the video transcripts of all sessions were reviewed and various points where interesting interactions seemed to occur were identified. A deliberate choice was made to focus on points where participants made a statement that indicated they had changed their belief or where conclusions could be drawn from the observation of the participant's behaviour in the environment. The theoretical framework of Activity Theory, presented in the following section, has been the overarching methodological framework that guides the aforementioned approach and has been considered a particularly well suited methodology for describing phenomena at various levels.

3.2.3 Activity Theory: a framework for analysis

Given its connections to constructivism and social constructivism, Activity Theory was regarded as a particulary relevant framework to situate and interpret the empirical studies for this research.

Activity Theory was adopted and adapted as one of many different approaches and theories of human-computer interaction to describe human interaction with machines (a comprehensive survey of older and recent theories in HCI can be found in Rogers (2002)). It is a philosophical framework that originates in the broader literature of Russian psychology of the 1920s and then the work of Vygotsky and his students (most notably Leont'ev (1978)). The central premise of the theory is based on the notion that human consciousness is subjective, as are the cognitive processes underlying conscious awareness and learning, and that these have their origins in a history of activity in a cultural context.

Bødker (1990) introduced Activity Theory to the HCI community through her book "Through the Interface" in an attempt to provide an alternative framework to HCI research that would address the growing need to move beyond the confines of cognitive science (Bødker, 1996). For years, cognitive science, which concentrates on information and information processing psychology, has been the dominant theoretical voice in HCI studies, based largely on the influential work of Card, Moran and Newell's Model Human Processor -a model used to explain and predict how a human responds to stimulus by reducing a user's interaction with a computer to its elementary actions and defining Goals, Operators, Methods, and Selection rules (Card et al., 1983). However, as a paradigm, the human information processor model, a deliberately simplified view of human cognition used to explain and predict how a human responds to stimulus, began to show its restrictions in understanding the full context of human activity with information systems. This is where activity theorists come in claiming to replace, or rather to radically expand, cognitive science (Nardi, 1996).

Although AT has a philosophical foundation it also aims to provide the field of human-computer interaction with a practical and scientific tool, attempting to bridge the gap between theory and practice. AT focuses on practice (doing and activity) and tries to understand consciousness and activity. Consciousness is located in everyday practice: you are what you do; what you do is embedded in the social matrix you are part of. Activity is also always situated in a context and impossible to understand without that context. A direct consequence of this is that everything (activity, development, learning, even consciousness) is a result of social interaction (Blumenthal, 1995). To put it differently, the keywords of activity theory are *context*, *situation*, and *practice*, a triptych that is also at the core of social constructivism as well as museum-based learning. "Rather than learning before acting, activity theory believes a priori that the human mind emerges and exists as a special component of interactions with the environment, so activity (sensory, mental, and physical) is a precursor to learning" (Jonassen and Rohrer-Murphy, 1999).

According to Activity Theory, the relationship between the individual and the world is not direct but mediated by the tools (e.g., technology) provided. Computers are a particularly interesting example of tools that are crucial mediators of human experience (Nardi, 1996). Activity is usually mediated by one or more instruments and is directed toward a certain object. Therefore, an activity is composed of a **Subject** (a person or group engaged in an activity) and an **Object** (for instance, a learning objective held by the subject), mediated by a **Tool** or tools (that could be material as well as mental). Engeström extended this systemic model with the social context, that is the Rules (that regulate actions and interactions), the Community (one or more people who share the objective with the subject), and the Division of Labour (how tasks are divided between cooperating members of the community as well as the division of power and status), thus forming the complete Activity System. In AT the systemic and dialectic nature of the complex and constantly evolving interrelationships between individuals and groups, their tools, their past experience, the division of labour, the community rules, and so on are illustrated by "triangle" diagrams such as Figure 3.4.

Engeström extended the activity theory hierarchical framework further to include the concept of **contradictions** (Engeström, 1987). Using this more extensive framework, he and his colleagues have analysed a range of work settings usually where there is a problem with existing or newly implemented technology (Rogers, 2002; Engeström, 1993). Identifying contradictions has been central to the analysis of user interaction for this research (Section 3.2.4).

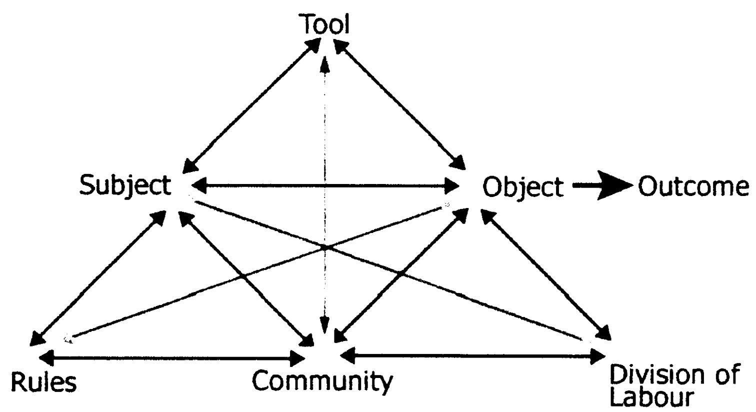

Figure 3.4: The complete Activity System model depicting the structure of human activity (developed by Engeström (1987, p.78)).

Activity level	Overall motive	building a house
Action level	Immediate goal	fixing the roofing
Operation level	Conditions or routines	hammering

Table 3.1: Hierarchical levels of an activity with an example of an activity, an action, and an operation according to Activity Theory

3.2.3.1 The levels of activity

As opposed to cognitive science, which focuses on the study of the individual as a separate entity, in AT the unit of analysis is an activity. An activity is seen as a system of human "doing" whereby a subject works on an object in order to obtain a desired outcome. An activity is modelled as a three-level hierarchy. An individual's behaviour is essentially presented as a hierarchical model that frames consciousness at different levels, in terms of operations, actions, and activities (see Table 3.1), together with a number of principles (Kuuti, 1996). In this multi-level hierarchical scheme, activities consist of actions or chains of actions, which in turn consist of operations (Nardi, 1996). Activity gives meaning to our actions and the same actions can appear in different activities. Each action is implemented through a series of operations (Bødker, 1996). The level of (automatic) operations is driven by the conditions and tools of action, the level of (individual or group) action is driven by a goal, and the level of (collective) activity is driven by an objective. In other words, the categories of activity, action, and operation can be analytically separated by asking why something takes place, what takes place, and how it is carried out (Bødker, 1996).

3.2.3.2 Contradictions and breakdowns

Because activities are not isolated or "disembodied" units, they can be externally influenced by other activities or changes in the environment. As noted, Activity Theory uses the term *contradictions* to indicate these changes or imbalances in the elements of activities (Engeström, 1987; Nardi, 1996). Use of the term *contradictions* is grounded in the activity theory and theory of expansive learning literature. Contradictions refer to disturbances, conflicts, ruptures, clashes, or problems that occur in an activity system or in the human practices being examined. Bødker refers to contradictions as *breakdowns* or *focus shifts* (Bødker, 1996). Breakdowns occur when the process is interrupted by something; perhaps the tool behaves differently than was anticipated, thus causing the triggering of inappropriate operations or not triggering any at all. A focus shift is a change of focus or object of the actions or activity that is more deliberate than those caused by breakdowns.

Humans are always in this process of working through contradictions, which can occur between the levels of activity, e.g. shifts in conscious attention from operations to actions. A contradiction occurs when, for example, an everyday activity (which may be subconsciously performed in a kind of "mechanical" manner through a set of operations) becomes part of our consciousness. This is what Winograd and Flores (1986) refer to when arguing that a breakdown always leads to a reinterpretation of the situation in the sense that objects appear from the background, becoming transparent or "ready-at-hand".

AT sees contradictions as sources of development (Nardi, 1996). Engeström (1987) views contradictions as the major driving force of learning and change. According to Engeström contradictions reflect a source of development or represent the presence of unfamiliar elements whose study is necessary so as to establish the kind of new developments that are taking place in that activity system. In order to understand the kind of new developments that are taking place in that activity system, there is a need to analyse the relationships that exist within and between the sub-activities. Specifically, the focus of this analysis is on establishing the means by which mediating tools (the Tool in the activity system model of Figure 3.4) support, access and interpenetrate the various levels of these sub-activities and their connectivity. Bødker (1996) considers breakdowns and focus shifts to be good pointers for understanding how a tool mediates (or does not mediate) when it is used for an activity. To her, a breakdown both leads to the appearance of transparent tools as objects, and to a conceptualization of the tacit operations involved (Bødker, 1990; Svanaes, 2000). This kind of approach can also help to reveal the communicative aspects of human activity at all levels of operations.

3.2.3.3 The use of Activity Theory

Activity Theory has been a recognised framework for analysing interaction between humans and computers. It can provide an organisational framework for such interaction in general and has been used as a conceptual aid in the research and design of constructivist learning environments. Nardi, to whom the popularisation of Activity Theory to human-computer interaction research can be largely attributed, regards AT as a "powerful and clarifying descriptive tool rather than a strongly predictive theory". Nevertheless, Activity Theory has been applied mostly to the design of systems (Blumenthal, 1995; Fjeld et al., 2002; Marsh et al., 2001; Jonassen and Rohrer-Murphy, 1999) rather than as a framework to guide evaluation.

The Virtual Reality projects for education that have used Activity Theory are limited to the work of Barab and colleagues (Barab et al., 2002). However, in that project, AT was used to describe the interaction within the classroom environment of an astronomy class, in which students used a VR world modelling tool to construct models of the sun, earth and moon during an eclipse. In other words, the activity that was described was not activity within a virtual world but with the tools to construct one. More recently, Activity Theory has also been used to analyse game players' activity (Oliver and Pelletier, 2005, 2006).

3.2.4 Adapting Activity Theory to this Research

The methodology adopted by this research for the analysis of the data draws on the organisational framework of Activity Theory described in the previous sections, which is believed to provide a suitable conceptual vocabulary for the description and interpretation of activity in virtual environments. There are various aspects of this research problem that make AT an appropriate methodology for studying it, including the novelty and context of the tool (a Virtual Environment), the richness of human activity in relation to it, and the dynamic nature of the goal of the activity (to achieve conceptual change).

Hence, for this research, the activity system model is formed as shown in Figure 3.5. The child participant is the subject using the features of the virtual environment as the tool to achieve the objective, which is to complete the learning tasks required by the activity within the virtual world. In order to carry out the tasks, the subject is required to follow rules (R) that have been set by the designers of the tool but also her own, self-constructed, rules that concern the learning content. Therefore, at a general level, the VR environment is the tool mediating between the subject and the object of activity. The tool itself can be broken down into various elements or renditions of the tool, such as the individual instances of system feedback or interactivity.

As discussed in sections 1.4 and 2.2.1, interactivity is considered only in terms of human machine interaction, and in accordance to the levels of interactivity in VEs presented in Table 2.1. In this sense, the only other human interacting with the subject throughout the activity in the VE is the observer (see Figure 3.3). The observer embodies the whole of the Community (that in a different context could include the family, peers, etc.) within which the activity takes place. This broader sociocultural and community context has not been regarded in further detail, as the interest is focussed on the effect of and the user's response to system feedback when interacting alone in the VE. Therefore, the focus is essentially Piagetian and constructivist - an experiment about a young human interacting with the material and technical world.

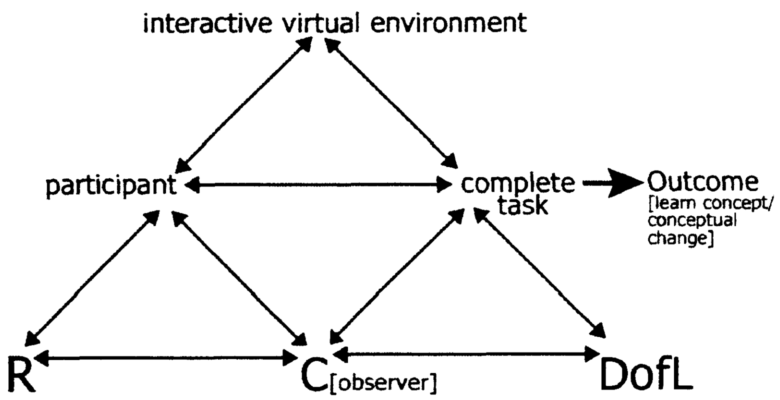

Figure 3.5: A general activity system diagram illustrating the Subject (participant), the Tool (interactive VE), and the Object (to complete the learning task), and their relationship for this research.

The first step in applying AT to the analysis of the experimental sessions in this research is to identify which parts of the user's activity when performing the tasks fit in the hierarchical level of Activity, Action, or Operation within the model of an Activity System. In other words, an attempt is made to organise the user's interaction with the virtual environment in terms of its correspondence to the level of Activity, to the level of Action, or to the level of Operation. It is assumed that user activity will be qualitatively different at the Activity level than at the Operation or Action levels, but that the interaction on all three levels is important in forming the relationship between interactivity and learning that is central to this study.

The theory is also applied to the specific objective of the research in evaluating user behaviour in immersive VR environments by placing emphasis on the identification of contradictions. As noted previously, AT uses the term contradictions to indicate focus shifts or breakdowns; in other words, changes and imbalances in the elements of activities. This concept has formed a core part of this research and serves as a point of departure when reviewing the data obtained by the empirical studies, especially the video data. In other words, the first thing to search for within the transcribed observations has been the occurrence of critical incidents or examples of contradictions between the elements of the activity system. The goal is to identify contradictions and breaks in the elements of the learner's activity that lead to indications of the learner's construction of meaning.

During the analysis, these incidents were closely described and categorised. As described later in chapters 4 and 7, where the interpretation of the exploratory study and main study are presented respectively, two categories of incidents provoking internal contradictions emerged: incidents caused by the unintentional intervention of the observer (for instance, the observer's questions caused the subject to change her course of action) and incidents caused through direct response from the system (e.g., an action that was not allowed by the system and communicated via system feedback caused the subject to think of alternative ways to handle a situation). Additionally, incidents that occurred through technical problems in the use of the system were also noted, however these were not analysed in detail, as the analysis of usability issues has not been the focus of this research. In fact, an effort was made to eliminate, as much as possible, the occurrence of such technical conflicts in the VE of the main study. On the other hand, the impact of unintended intervention by the observer due to the data collection process of the subject's 'thinking out loud' during observation, is an instance of community intervention or 'breakdown' on the activity of the subject. These incidents, according to AT, may indeed impact on relevant conceptual learning as an inherent part of the experience, since, in activity theory, thinking, feeling, acting, and relating to another person in the context, are all part of the same process. However, what is of utmost importance to this research is the instances that are caused by the tool, for example focus shifts or breakdowns triggered by system feedback that, in turn, can provoke a change in conceptual understanding. These are the kinds of instances where emphasis is given for further analysis.

In addition to the analytical tools provided by Activity Theory, that allow for describing the instances of activity between the user and the system, a coding scheme that would help to pull together and then subdivide the data into coherent categories, patterns, or themes was sought. A variety of coding schemes from grounded theory (Glaser and Strauss, 1967), protocol analysis (Ericsson and Simon, 1993), verbal analysis (Chi, 1997), interaction analysis (Jordan and Henderson, 1995), conversation or discourse analysis (Cohen et al., 2000, p.298), sequential data analysis (Bakeman and Gottman, 1997), and emergent coding or content analysis (Krippendorf, 1980) were considered. What these have in common is a concern with handling dynamic, event-driven behavior that emerges from oral or written language as it unfolds over time, and with capturing the essence of that behavior in summary structures, i.e. conceptual categories and themes. Finally, a simple form of content analysis was used to structure the cases where interesting incidents occurred thematically. Content analysis involves identifying coherent and important examples, themes, and patterns in the data (Patton, 1987). In other words, observations or quotations that go together as examples of the same underlying idea, issue, or concept are classified into some meaningful and manageable themes. Strictly speaking, content analysis is primarily a quantitative analysis method known to involve counting the occurrence of keywords in text and messages (Krippendorf, 1980). However, it can extend beyond word counts and frequencies to encompass more general content and higher level categories. In the case of this research, content analysis is used in its broader qualitative and simpler form; the themes that emerged from the incidents in the data were either common learning problems or cues/features of the system that prompted participants to act or respond in similar ways. On this basis, examples of individual participants' activity were chosen to illustrate certain aspects and instances that related to each theme (Cohen et al., 2000, p.181).

In a nutshell, the adaptation of the methodological framework of Activity Theory to this research follows a pragmatic approach that can be briefly summarised as follows: real-time observation recorded on video captures verbalisations and the participants' interactions with the virtual environment, which are examined in a process of identifying interesting incidents or contradictions. These are then described in terms of their effect in the activity system, and the descriptions are collected in categories that are formed through an emergent thematic coding. The pre-tests, post-tests, and log files are analysed quantitatively but are also used to support the qualitative analytical process further, based on the mandate to triangulate methods that can offer complementary perspectives. A first application of this methodological approach was carried out as part of the exploratory study that is described in the next chapter (Chapter 4).

3.3 Summary

This chapter has described the methodological approach guiding the data collection process (Section 3.1) and data analysis (Section 3.2) for this research. The need to combine various methods and techniques has been identified for various reasons, including the novelty and intuitive nature of the tool, and the fact that the participants are children. In particular, for data collection, a multitude of different methods is employed, including direct observation, pre- and post-tests, semi-structured interviews, and computer-generated log files. In terms of data analysis, a mixed methodology of quantitative and qualitative methods has been chosen. The pre- and post-test scores were analysed using statistical methods (Section 3.2.1). The observational and interview data were analysed qualitatively, based primarily on Activity Theory as a research method for describing and operationalising the relationship between the subject, the tool and the goal of the interaction (Sections 3.2.2 and 3.2.3). Of particular use to this research has been the identification and examination of critical incidents or contradictions, which, according to the Activity Theory framework, can provide manifestations of learning. These were then structured thematically, into themes that emerged from the data (Section 3.2.4).

In the next chapter (Chapter 4), an exploratory study, which was designed to test the above methodology and prepare for the main evaluation study (Chapter 6), is described and analysed.

Chapter 4

Exploratory Study

The overall goal of this research is to examine the relationship between interactivity and learning in a VE and determine if and how interactivity enables learners to develop deep understanding of a topic. In order to provide evidence of the effect of interactivity on learning, a series of empirical evaluations were carried out, starting from the exploratory study described in this chapter.

For this first study, an exploratory approach was adopted for a number of reasons. First of all, an exploratory observation-based design was chosen because few assumptions need to be made at the outset regarding what is important in the work to be studied. The complex, contextualised nature of the topic and the medium led the researcher to consider that, at this stage, it was premature to run a precisely defined experiment because of the large number of variables involved (levels of interactivity; conceptual, factual learning; different learning styles), their complex nature (learning, interactivity) and the differing content and contexts (abstract or concrete; school or informal education). Thus, for the early stages of the research, a small set of experiments that allowed the observation and analysis of such situations was considered most appropriate. The purpose of these studies was to formulate the main study, described in Chapter 6, by identifying the different elements that would comprise the design of the experiments to follow.

Secondly, no established frameworks were found in the existing literature that could advise as to the kinds of information that should be gathered from empirical evaluations in order to determine the effectiveness of interactivity in a virtual environment and thus help improve understanding of how learners interact in virtual environments. Hence, the exploratory study was intended to help formulate a methodological and analytical approach capable of relating the theoretical underpinnings explored in the literature review to practical methods.

Finally, this study was planned to act as a trial for the practical aspects of the method: to establish techniques for subsequent studies; to identify early-on any potential problems that can occur in the running of such experiments (for instance, experiment design issues, virtual environment usability issues, practical and ethical issues related to handling of the participants, and so on); and then to develop and refine the design and method.

In other words, the exploratory study described in this chapter forms the first in a sequence of two testing phases, which start from this early experiment that aims to explore the medium and the method before proceeding onto the main evaluation study. The following sections discuss the design and procedures of the study (Sections 4.1, 4.1.1, 4.1.2, and 4.1.3), and the analysis of the observations using Activity Theory (Section 4.2). The chapter concludes with a discussion of the outcomes of the exploratory study (Section 4.3), and in particular its contribution to the design of a virtual environment for the main study, described in Chapters 5 and 6 respectively.

4.1 Experimental Design

Due to the exploratory nature of this first study, a relatively simple learning problem was selected, which involved learning about the characteristics and differences of ancient Greek columns. The learning activity involved the construction of ancient columns in virtual reality, through the placement and manipulation of their parts. It was expected that participants in the virtual environment would benefit from the form of representation of the learning content (e.g., natural proportions of parts, surrounding context) and the ability to manipulate elements. Furthermore, it was expected that system feedback, although very limited in this particular implementation, would enhance the learning process.

Because this experiment was exploratory in nature, a simplified version of the methodology described in Chapter 3 was followed. A virtual environment involving a set of construction tasks was developed. Each participant had to perform the tasks within the virtual environment while the participant's interaction in completing the tasks was observed and then qualitatively described with the use of Activity Theory.

The main method of data collection followed during this first study involved the researcher acting as observer and interviewer. The intention during this process was for the observer to be as unobtrusive as possible but it proved difficult given that the participant had to be asked questions while interacting with the virtual environment. This approach, however, was meant to be flexible, so as to allow for adjustments to the process of data collection and analysis that would be followed in the main experiment, described in Chapter 6. Pre- and post-tests or other questionnaires were not used, and the interviews with participants were of a very informal, conversational tone.

4.1.1 Experiment tasks

A virtual environment was designed with three separate tasks that were performed in sequence (from A to C) with breaks in between for the participant to rest. The tasks were designed to follow a tiered structure, requiring a slightly different and progressively more complex activity, which would require greater thought for completing each one. All three tasks involved a construction activity with the placement and manipulation of column parts. Each column in each of the tasks was made of a total of 6 pieces, including the capital (column head) and column base. Two types (called "orders") of columns were used: a column of Ionic order (the one with the elaborate "scroll" shaped capital) and a column of Doric order (Figure 4.4). In each task the column bases were positioned in the centre of the virtual space, which corresponded to, approximately, the middle of the floor of the physical room-sized virtual reality system (CAVE). The column bases were the only parts in the environment that could not be moved by the participant. The other parts, when pointed at, displayed a red bounding box, which meant that they could be selected with the press of a button and "attached" to the participant's hand. They could be "dropped" by pressing the same button. The goal or objective of the activities was for participants to *learn about columns*, i.e. to be able to distinguish the order and to understand the differences between the column parts and how they achieve symmetry.

The first two tasks involved only selection and placement of the virtual column pieces. According to the definition of interactivity adopted by this research (Section 2.2.1), such manipulation of the environment or parameters of the environment represents a moderate level of interactivity (but perhaps one of the most advanced metaphors of interaction in typical VR applications). The final task added an extra level of interactivity by allowing further manipulation (resizing) of the pieces. The tasks were designed to be as simple as possible yet to try and invoke participant interaction in such a way that it could potentially map to the Operation-Action-Activity levels of the AT framework (Section 3.2.3). As mentioned, the intended learning goal concerned understanding the differences between columns and the importance of scale and symmetry. However, ultimately, the purpose of the exploratory study was not to look exclusively at whether or not participants achieved this goal, but at the range of things that they did (and maybe even learned) in the process and which could inform the design of the later study and the method of analysis.

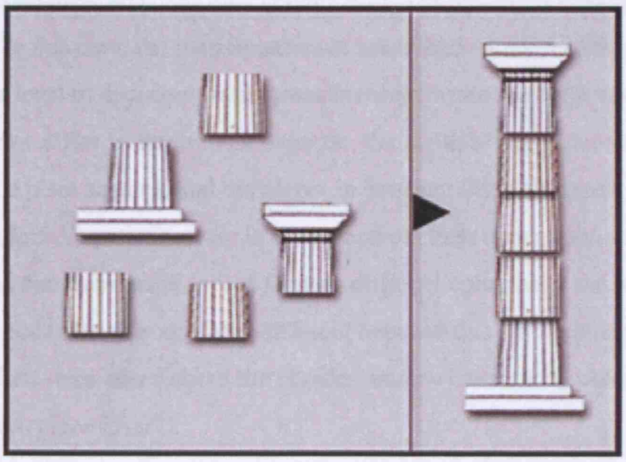

Figure 4.1: Concept sketch of Task A - constructing a column through placement of available parts.

The tasks were performed in sequence, starting from Task A, then proceeding to Task B and, finally, completing the experience with Task C. The sequence reflected an increase in complexity as well as in the interactive features available.

Task A. The first environment was a simple 3D puzzle; the participant must construct the model of a Doric column by picking and placing/positioning the pieces that are provided (Figure 4.1). The participant was told to do whatever she thought is appropriate and to inform the observer when she believed that she had completed the task and felt happy with the result. No time limitation was given, but the participant was encouraged to move on if she spent too much time on a task that was frustrating or not very important (such as precisely aligning one piece to the other). The main questions asked during this task attempted to identify if the participant was using any specific criteria when choosing the pieces, if she considered all the pieces to be the same or, if not, what she believed was different.

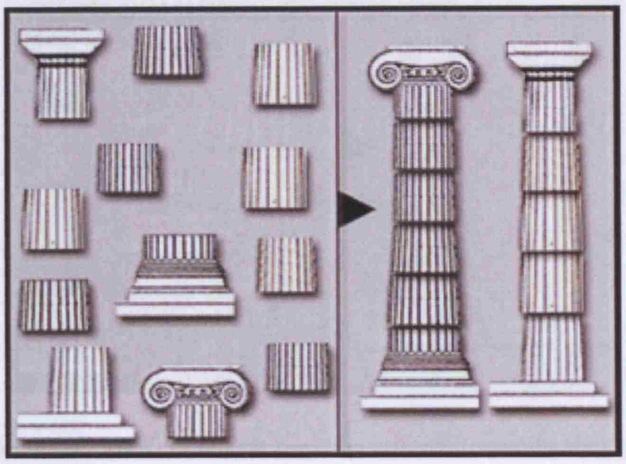

Figure 4.2: Concept sketch of Task B - constructing two different columns through selection and placement of available parts.

Task B. Similarly to task A, task B required the participant to construct models, only this time it was two different columns, one Ionic and one Doric (Figure 4.2). The pieces for both columns were randomly placed on the ground. In this case, the participant must select and decide which part belonged to which column, hence an extra level of decision-making was involved when the child was performing this task. Ionic and Doric columns differ in three main aspects: the capitals (the most obvious difference), the bases (the Doric being a plain square), and the pieces in between (the Doric ones being thinner than the Ionic pieces and with a less dramatic increase in diameter from their upper part to their bottom part). The participant was not told that there were pieces for two different columns at the outset but was asked to describe what she saw and if she saw anything different between this environment and the previous one. During the task, questions were asked about the choices made when making comparisons (for example, "why did you choose that piece first?").

Task C. The final task was designed to provide parts of two different columns, as in task B, only the pieces were not in the correct size (Figure 4.3). The participant had to construct the two columns and resize the pieces when necessary. Prior to the assignment of Task C, the participant would be given a simple training environment in which she would practice how to resize a box by pulling on its edges with the interaction device.

However, it was judged that this task was considerably more difficult than Task B and that the interface became rather complicated, so it was decided that Task C would involve the construction of one column (the same as in Task A) but with the provided pieces to be noticeably different in size. The participant was not told this at the outset and was left to perform this task until she identified the difference in size. If the participant expressed the wish to be able to resize a piece, or seemed confused as to what was going on, she was then shown how to resize a piece and told to do so according to her own judgement. Questions were asked about the degree of change applied to each piece and the reasons for deciding on scaling one piece over another.

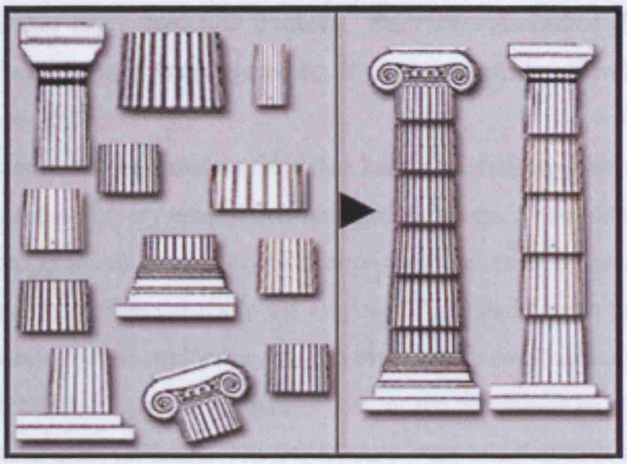

Figure 4.3: Concept sketch of Task C - constructing two different columns through selection, modification (scaling), and placement of available parts.

Upon completion of each column in Tasks A and B, the researcher was able to see if the pieces were placed in the correct order (the pieces were colour-coded and the colours were revealed with the press of a "secret" button). Appendix A includes the result of each participant's activity.

4.1.2 Participants and apparatus

The exploratory experiments were conducted with three participants aged 7, 9, and 12 years old, on different days (see also Appendix A). The participants were selected based on their age and flexibility (i.e. they were children whose parents trusted them with the researcher for as long as the study went on).

The virtual reality system used for testing was a CAVE-like display, as described in Section 3.1.3. The interaction device was programmed according to the tasks. For the first two tasks only one button was used both for selecting and letting go of virtual objects. For the third task, two additional buttons were used for scaling virtual objects (left button to increase size, right button to decrease; every button click represented a 5% change in scale). Navigation within the VE was not required thus the joystick on the interaction device was not activated for any of the tasks.

A short training session on the use of the buttons on the interaction device was provided within the virtual environment of the first task. No specific time limitation was imposed on the participants for performing the actual tasks. Overall, the time the participants spent in the virtual environment performing the tasks ranged from 45 to 75 minutes, including two to three 10-minute breaks. A think-aloud technique was encouraged in order to facilitate observation and analysis, so the participant was occasionally reminded by the observer to explain-while-doing.

4.1.3 Procedure

An introductory conversation took place with questions that aimed at giving a feel of the participant's relationship with technology along with an attempt to make each participant feel more comfortable with the observer. First of all, each participant was asked what year in school they were in and if they enjoyed school. Then they were asked to describe if they use computers at school or at home, if they play computer games and if they had a particular favourite. They were also asked if they had experienced a virtual environment before and if they enjoyed it. If they responded positively, they were asked to describe their experience further.

In practice, these conversations lasted no more than 2 minutes; they were informal, without a particular structure, and included some very general non-directive questions. It sometimes proved unnecessary to ask all of the questions explicitly since the conversation tended to cover the ground of its own accord.

The participant was then informed about the purpose of the study and a brief explanation of the tasks was given. The tasks for these exploratory studies involved the construction of ancient columns, as already described in section 4.1.1, and the objective was for the participant to learn about the different types of columns and their characteristics. The participants were told that they would perform this experiment in order to help the researcher improve some computer tools and this is why their participation was very valuable. It was pointed out to them that the experiment tasks were not an exam, in that there was no right or wrong answer, and that their only obligation, besides performing the task as best as they could, would be to remember to think "out loud" and describe their every action, even if it did not seem important to them (examples such as: "now I pick up this piece and I am putting it here..." were given to illustrate the technique). Before explaining the tasks, a few questions related to knowledge of the content were asked. The researcher showed images (on paper) of 3D models of the columns and asked the participants if they recognised them and if they could identify differences (Figure 4.4). If they could, they were asked if this knowledge was acquired from school or from visits to museums or archeological sites.

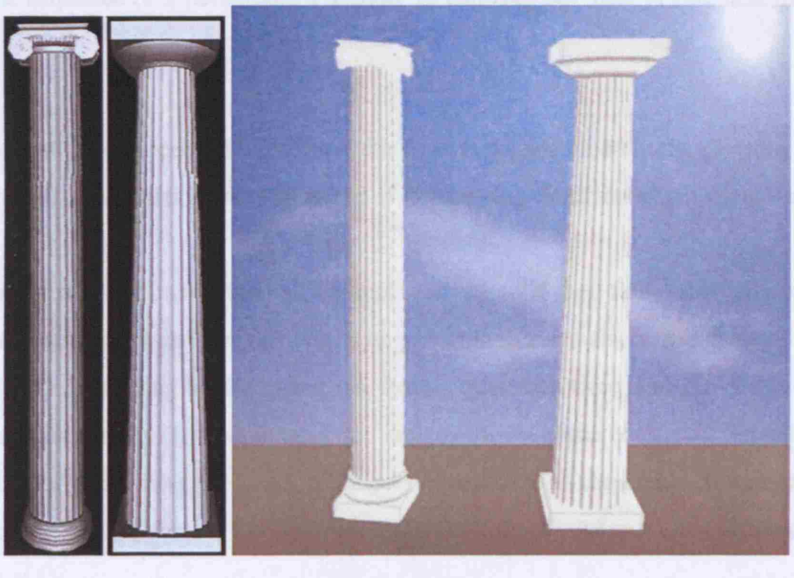

Figure 4.4: Renderings of columns of two different orders, Ionic and Doric, were shown to the participant (left). The columns after their successful construction in virtual reality (right).

Following this introductory procedure, the participant was shown into the virtual environment where the researcher demonstrated the use of the interaction device that would be used to complete the assigned tasks. The virtual pieces could be picked up by approaching them (physically walking if required) and pointing the wand in their direction. When a red bounding sphere appeared, the device button could be clicked to attach the piece to the participant's hand; when the button was clicked again the piece was detached. The participant was asked to practice this operation with the virtual objects of the first task, by picking up and letting go of each piece. No other functionality was shown to the participant at this time.

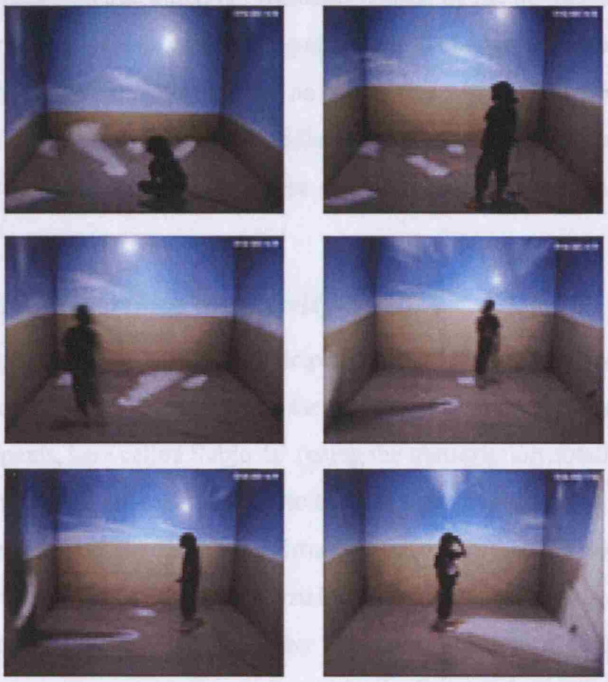

Figure 4.5: The sequence of a participant's activity in carrying out Task A (the task of constructing a column).

The participant then proceeded to perform the three tasks described in the previous section (Figure 4.5). Between tasks, the participant was asked if he/she was tired, in which case a short break was granted.

After completion of all tasks, the participants were asked if they found the tasks to be difficult or simple and to explain what was more difficult. The participants were also asked if they thought they had learned something. Depending on the responses, further questions were asked to determine factors that may have influenced activity (for example, if the images shown at the beginning played any role in the participant's way of completing the tasks, if the participant tried to remember or replicate the columns that were seen in the pictures before the experiments, if these were used as guides for the decisions made, and so on).

A detailed description of the participants' activity in the virtual environment can be found in Appendix A.

4.2 Analysis of Exploratory Study

The method for analysing the observational data collected from the three participants of the exploratory study followed the process described in section 3.2.4, which is largely based on the organisational framework of Activity Theory. Activity Theory, as noted in section 3.2.3, uses the term *contradictions* to indicate problems, ruptures, breakdowns, or clashes; in other words, changes and imbalances in the elements of activities (Nardi, 1996). When reviewing all three cases of the exploratory study, critical incidents or examples of contradictions occurring in the system were sought. These were categorised into the following three groups of incidents that emerged: incidents caused by the unintentional intervention of the observer (i.e. the observer's questions caused the participant to change her course of action); incidents caused through direct response from system (i.e. an action that was not allowed by the system caused the participant to think of alternative ways to handle a situation); and incidents that occurred through technical problems in the use of the system. These categories are presented in detail in the following section.

4.2.1 Interpretation according to Activity Theory

In the excerpts that follow, the relationship of participant and activity is examined by using AT's activity system notations. The components that constitute the activity system for this analysis primarily include each of the three participants, here called Subjects[1] (using the transcription notations S1...S3), the Object (in this case, the construction of columns leading to the learning goal/objective which is learning about different types of columns), and the Tool (the Virtual Environment). On a second level, the relation between subject and object is mediated by the participant observer who in this case also represents the Community (and is indicated by **C** in the text), by rules, and division of labour (Nardi, 1996). The Activity System diagrams to illustrate these relationships are shown below (Figures 4.6 and 4.7):

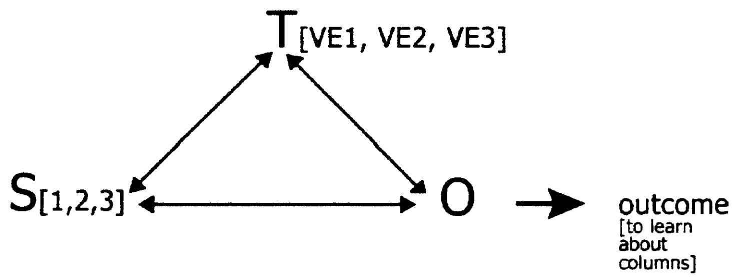

Figure 4.6: A general activity system diagram illustrating the relationship between Subject (S), Object (O), and Tool (T) for the exploratory study.

Each Subject [S1 to S3] uses the Tool [the Virtual Environment 1, 2, and 3 that corresponds to each of the three tasks] to achieve the Object/Objective [constructing columns]. The outcome [to learn about columns] is what the Community expects from the Subject.

The Community sets Rules for achieving the tasks. Each Subject understands the Rules in his or her own way (i.e. they may not be the same as the Community's).

The focus was given on excerpts where instances provoking internal contradictions seemed to occur. These were categorised as incidents caused by technical problems, incidents caused by observer intervention (which will be called "extrinsic" feedback) and incidents caused through some kind of system

[1]For a detailed account of the participants' activity in the virtual environment, see Appendix A.

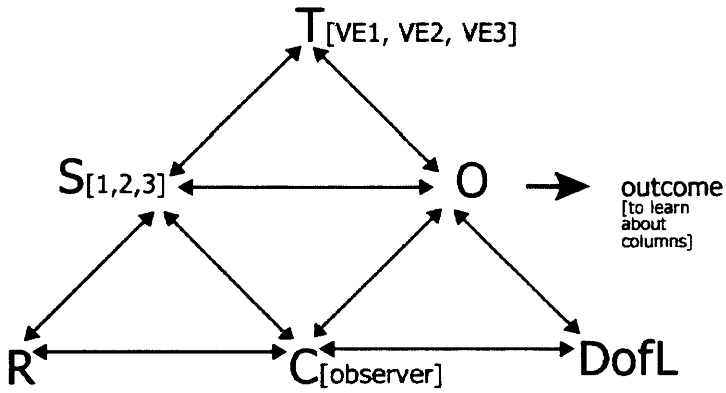

Figure 4.7: A general activity system diagram extended to include the relationship between the three main components (S, T, O) and the Rules (R), Community (in this case the observer), and Division of Labour (DofL).

feature or response ("intrinsic feedback").

4.2.1.1 Incidents caused by technical problems

A number of incidents caused by technical or usability problems occurred during the participants' interactions with the system. Besides the technical breakdowns that occurred twice (where the system had to be reset), there were a few cases where the participants were unsuccessful in picking or placing a piece due to the fact that it was occluded by another piece or the children were not able to reach the top of a column in order to place the capital. In some of these cases the observer had to intervene in order to help resolve the problem or speed up the process. For example, during S1's activity for Task B, the observer had to move in and reposition some of the column drums so that S1 could reach them. Since navigation was disabled, a few pieces that were farther away in the virtual space were not easily accessible by the participant. The activity system diagrams that follow illustrate this technical/usability breakdown, where the problems that the subject (S1) had in using the virtual environment (shown as a break between S1 and T) caused the observer (C) to intervene (shown as a breakdown in the Division of Labour) in order to resolve the contradiction (Figure 4.8).

Overall, the participants learned a number of things about using the system and this technical learning was apparent after the first task since the time they spent on trying to pick and place the virtual objects was reduced, as was their frustration, and they generally seemed much more comfortable in carrying out their tasks. However, this kind of technical learning does not represent the kind of learning that this research has set out to explore. Technical breakdowns such as the one illustrated above, where the contradiction occurs between S and T or where there is a breakdown in the division of labour (i.e. the observer steps in to help with the handset, or to re-set the system), although taken into account during the analysis of this exploratory study, are not the kind of incidents that interest this research because they do not concern relevant conceptual learning.

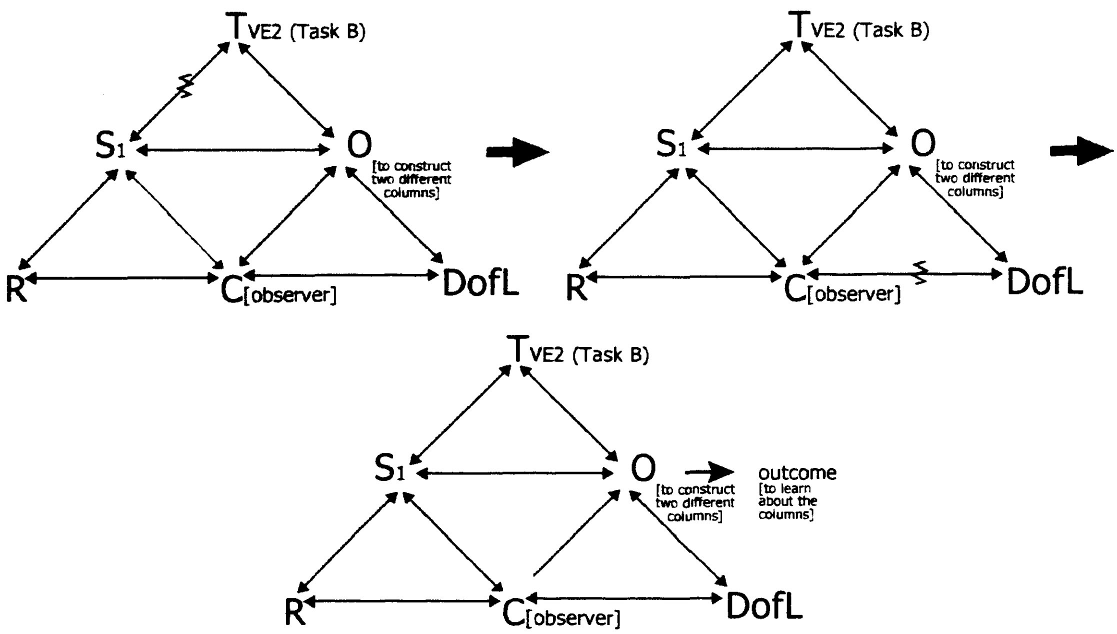

Figure 4.8: An activity system illustrating the observer's intervention in resolving the contradiction.

4.2.1.2 Incidents caused by observer intervention

As mentioned, the observer's role was to remind the participants to think out loud by asking questions at instances where participant activity seemed to entail some kind of contradiction, and to help with the use of the system if problems occurred. Any other intervention by the observer that may have caused the participant to change her course of action was unintentional. However, such instances of unintentional intervention were recorded for the purposes of this exploratory study.

The dialogue below is an example of such an instance. It occurred during Task B, after S1 had incorrectly constructed two columns, the Ionic with an extra piece that normally belonged to the Doric.

1. **C.**: Why did you choose some pieces over others?

2. **S1**: I chose the thicker pieces for one column and the thinner for the other.

3. **C.**: And how did you decide to put the thick pieces on this column [*showing Doric column*] and the thin pieces on the other one?

4. **S1**: Because one base is thin and I put the thin pieces there.

S1 was very confident of her reply and, technically speaking, her reply was correct in terms of what she should have done. This indicates that, in this case, she understood the Rules. However, the thick piece remained in the column with the thinner pieces, so what she claimed to be doing in theory was not done in practice. The intervention did not seem to have any effect at this point, and further questions were asked.

5. **C.**: So do these look right to you?

6. **S1**: They look funny.

7. **C.**: How so?

8. **S1**: They are not straight.

9. **C.**: That's all?

10. **S1**: And one is smaller and shorter; the other is taller and long.

11. **C.**: Why?

She stood back to think about what she had said before (which indicates that she indeed had not made a conscious decision when acting). She then observed the columns more closely, identified the misplaced piece and corrected her columns. The observer's intervention, although not intended as a pedagogical prompt, caused a change in behaviour.

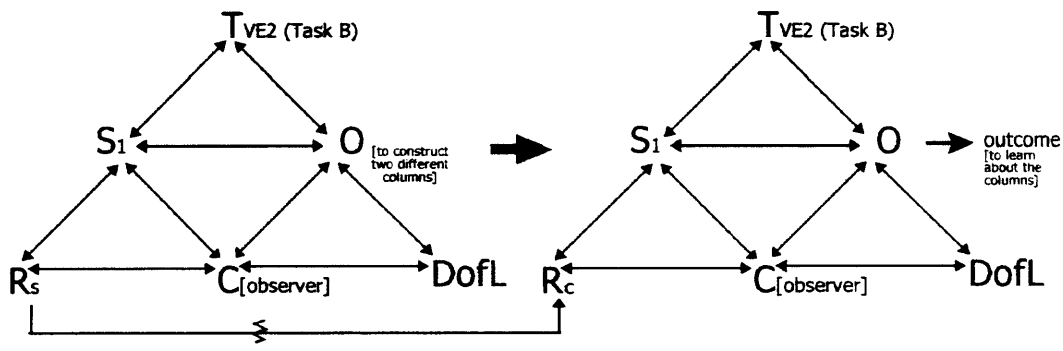

Figure 4.9: An activity system illustrating a contradiction between the Subject's understanding of the Rules and the use of a different rule set.

In S1's view, the Object (to construct two columns) was achieved. The subject explained the Rules (that all thick pieces go to one column and all thin to the other) to C. There was common understanding of the Rules between C and S1; however, S1 did not use these Rules (Rc) to achieve the Objective. This indicates a break between what the Subject understands as Rules (Rs) and the action she makes to reach her goal, which is resolved with C's intervention (Figure 4.9).

In this case, it is argued that this change of behaviour is an indication that learning occurred. However, one cannot be certain of the exact outcome (if deep understanding about the differences between columns was achieved) since no other methods for investigating it further were used (such as, asking more specific questions, completing a post-test, and so on). Moreover, the learning that did occur was a result of the conversation between S1 and C and not purely of S1's activity with the system, even though the activity with the system was the material that triggered the discussion between S1 and C.

4.2.1.3 Incidents caused by system feedback

The system was not programmed to provide any explicit feedback. However, it was designed with certain features that provided intrinsic feedback, such as the fact that the column bases could not be moved. This was enough direct feedback to provoke some interesting incidents. Furthermore, this is the kind of feedback this research is interested in examining since it illustrates the system's interactive capabilities. The series of examples given below represents all of the incidents in this category.

Example 1

The following occurred with S2, at the beginning of the construction of the column in Task A:

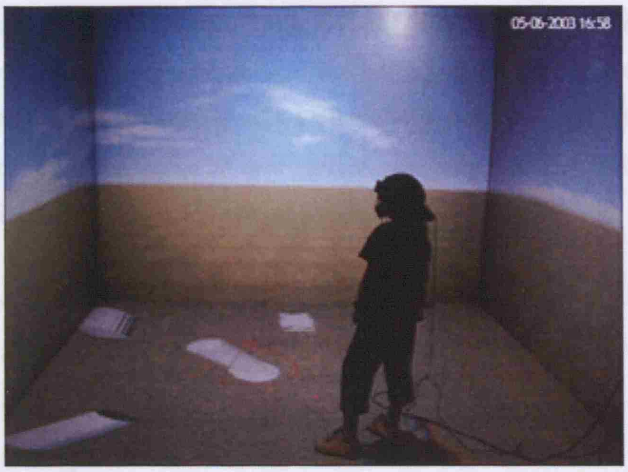

Figure 4.10: S1 while constructing a column through placement of available parts.

Figure 4.11: S2 while completing the Ionic column by placing the capital on top.

12. **C.**: Why did you decide to start with that piece over any one of the other pieces?

13. **S2**: It doesn't matter... because they all look the same.

He reaches the top piece and sees that it protrudes, so then starts rearranging the pieces.

14. **C.**: What are you doing now?

15. **S2**: The column is not straight. I think this piece [*top piece*] must go to the bottom... It is protruding.

16. **C.**: You said before that all the pieces are the same.

17. **S2**: Yeah.

18. **C.**: So did you change your mind?

19. **S2**: Every drum is different at the top than at the bottom. The top top piece is the thinnest.

He proceeds in carefully examining both ends of all pieces before rearranging them. He then places the pieces and completes the column correctly (Figure 4.11). S2 follows a complete interaction circle:

he has an intention, he performs an action, he observes and evaluates the effect of an action (examines, places, turns, compares each piece), and he modifies/corrects the action based on the results of his assessment. His observation of the system's rules guides him in evaluating his actions. S2 has created an initial understanding of the Rules which he then revises, assessing for himself the contradiction within the system and resolving it in order to achieve the objective (Figure 4.12).

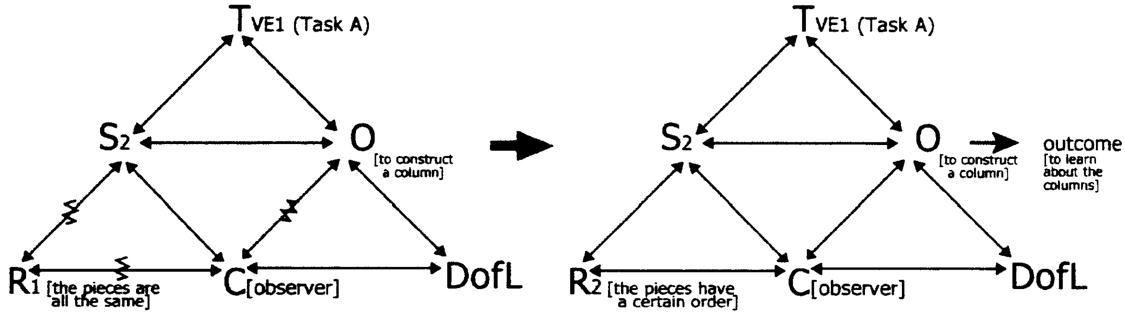

Figure 4.12: An activity system illustrating S2's understanding of the Rules and then self-reassessment.

On the other hand, in the previous case, S1 and C initially also have different understandings of the Rules, but that only becomes apparent when C asks S1 questions which eventually cause her to reevaluate the Rules (Figure 4.9). In both cases, there is a breakdown or contradiction in behaviour and it is this progression or process of resolving contradiction where it is argued that learning is occurring. The difference between S1 and S2 is that S1 changes behaviour when there is intervention from C, not from interaction with the system. This difference where S2 self-corrects whereas S1 requires intervention seems to be consistent with Vygotsky's Zone of Proximal Development (ZPD) (Vygotsky, 1986), which concerns the internalisation of social rules. S2 is already able to internalise the Rules whereas S1 is not able to do the same without discussion with the Community. S1 is within the ZPD, i.e. she can learn with support from a more able peer, but is not yet able to complete the task unaided.

Example 2

S3 in Task B had completed the construction of the two columns, only the Doric was shorter than the Ionic by one piece. He found the wide piece in the Ionic and moved it to the Doric.

20. **S3**: I see that something is not right here.

21. **C.**: Which piece is not right?

22. **S3**: That [*showing a wide piece in the Ionic column*].

23. **C.**: Why?

24. **S3**: Because it is thicker.

Both columns now have the same number of pieces. However, these are not necessarily the correct pieces. A bit later, S3 realises this:

25. **S3**: I found a mistake.

26. **C.**: What mistake?

27. **S3**: This here [*showing a piece on the Doric*] doesn't belong here; it belongs down there

[*exchanges the piece with one in the Ionic*].

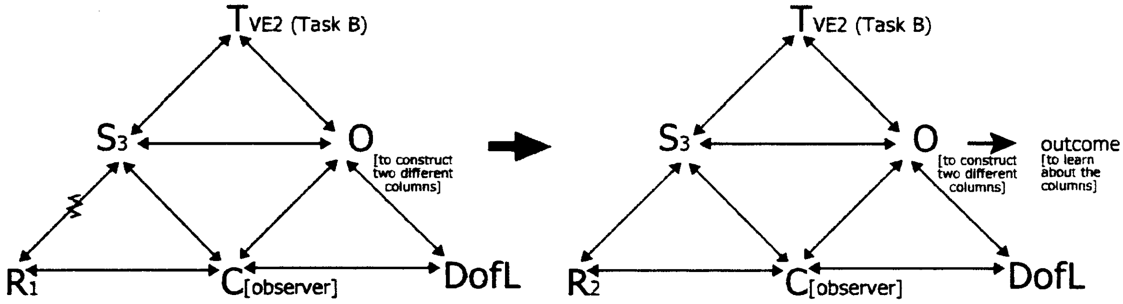

Figure 4.13: An activity system illustrating S3's revision of the Rules following self reflection.

In an activity system, this is shown as a break between S and R_1, leading to a new system with no break between S and R_2 (the revised rules). The conflict between the subject and the rule set is resolved after a conceptual revision of the rules (Figure 4.13).

This is an example where the subject spontaneously changes the way he acts, based on what he observes, on reflection or consideration. He proceeds in correcting his mistakes as a result of what he sees (what "looks right") and not as a consequence of the interactive properties of the system. This conceptual revision of rules may be an indication of learning but is not an example of learning that arises from the unique features of VR, the kind that explores the effect of interactivity, as a VR property, on conceptual learning, because any visualisation tool could have prompted such a change.

Example 3

In Task B, S2 reached the point where he had to find the base of the Doric column, from which he would start building that column. He wasn't sure whether the base was the square flat piece which lay flat on the ground or another piece that looked like it but was more curved (which, in fact, was the capital). He seemed to have solved this when he realised that he could not pick up the base; however, he was not able to explain this well.

28. **C.**: How about those pieces? [*referring to the Ionic and Doric column bases*]

29. **S2**: [*showing in the general direction*] On one side is one base and on this side is the other base.

30. **C.**: How did you conclude this?

31. **S2**: Well, this base [*pointing to the Ionic column base*] is definitely one base because I saw it in the previous (task). And this [*showing the Doric column base*] is the other base because this other piece [*showing the Doric column head which he originally thought may be the base*] has a kind of a curve.

32. **C.**: So what are the differences between the columns?

33. **S2**: They are of different order.

34. **C.**: How do you know this?

35. **S2**: From the head of the column.

36. **C.**: Only from the head?

37. **S2**: And from the base. But also from the pieces, in one column they are bigger than in the other.

38. **C.**: Is this something you just realised or did you remember it?

39. **S2**: I just realised... well I had seen the photograph, but I didn't remember if one was bigger.

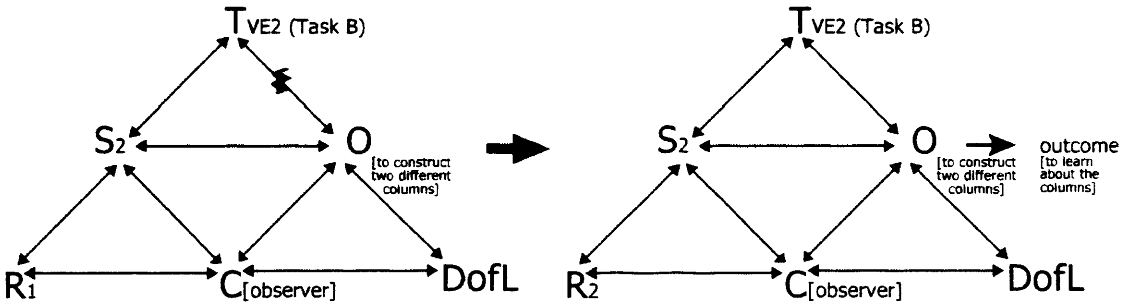

Figure 4.14: An activity system illustrating the contradiction between the Tool and the Object, which leads to S2's revision of the rules (from R_1 to R_2) to resolve the contradiction.

S2 can use the Tool but the Tool doesn't let him achieve what he sets out to do. Specifically, since he does not know how to distinguish between bases and capitals, he tries to move a piece that the system will not allow to be moved. Within this action, his use of the tool is technically correct, but its target is not. The contradiction that arises is thus between the Tool and Object. Rather than resolving this breakdown directly (for example, by using a different tool or learning a new technical approach) he changes his expectations, he revises what he wants. This is represented in Figure 4.14 by a change in the rules: as indicated in the excerpt from the transcript, he reviewed the differences between pieces in the light of his failed attempt to move them. From this reflection, he learned to distinguish between capitals and bases and between Doric and Ionic columns. The feedback from the system alerted him that not all pieces were the same, so that he then attended to other differences between pieces. This revision of rules by the participant is a clear indication of conceptual change, as defined in 2.1.1.1. In this case, the restructuring, or cognitive reorganisation of an existing explanatory structure into a new one, can be described as the revision of personal beliefs through the acquisition of the rules of the community.

Example 4

The same type of intrinsic feedback (that the column bases could not be moved) aided S3 in changing his course of behaviour. For Task A, S3 started constructing the column from the capital, which he placed in the air and then began building downwards by placing the drums underneath. He had managed to squeeze the last drum under the others and attempted to pick up the base, which was the last piece left and was located on the floor to the side of the column that he was constructing.

40. **C.**: How do you see that this piece goes at the bottom rather than the top.

41. **S3**: It's the last piece.

42. **C.**: How do you know that it is the last piece?

43. **S3**: Because I put that one [*showing the bottom last column drum*] and saw that there is no other

one that fits below it... Anyway, you can tell it's the last piece.

44. **S3**: [*trying to pick up the base*] It is glued on the floor...

45. **C.**: Why would it be glued on the floor?

46. **S3**: So it doesn't show... Oh! So that I can put the other pieces here.

He started taking apart the column he had constructed in the air and constructing it piece by piece on top of the base. He de-constructed the column he had made in the air by starting from the top drum, which he placed at the bottom (directly over the base) and every other piece on top of it until he placed the capital. The "Oh!" is the "Eureka" moment that both triggers his change in behaviour and indicates a change in his conceptions. Furthermore, in the tasks that followed (Task B and C) S3 identified the bases immediately, having learned and remembered from Task A that the bases do not move, and started constructing the columns from the bottom working up (Figure 4.16).

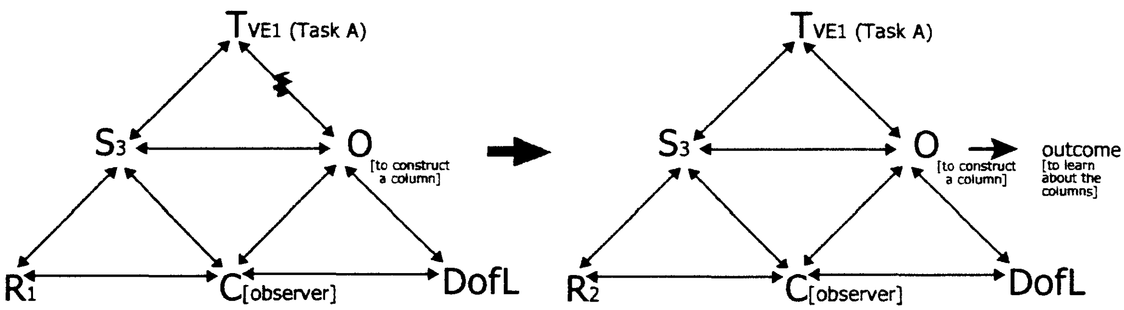

Figure 4.15: An activity system illustrating the breakdown between the Tool and the Object, leading to S3's revision of the rules and resolution of the breakdown.

In an activity system, the above incident would be illustrated with a break between T and O, which is resolved not by S3 learning how to use the tool better, but instead by him realising that he is not supposed to do this. Thus, it is resolved by a new system involving a revised rule set, R_2. In other words, in this example, the subject changes the way he acts after the system prevents him from doing something. As in the previous example, a revision of personal beliefs takes place, through the acquisition of the rules of the community. This, arguably, is an example of conceptual learning from interaction with the VR system, and it is the kind of incident that this research is most interested in examining.

Overall, the incidents mentioned above showed evidence of some kind of learning; however, in most cases, it was not the kind of learning that this research has set out to study, as defined in section 2.1 (conceptual learning or the internalisation and restructuring of preexisting concepts). In most examples, the level of evidence that relates to conceptual change either small or was not learning that resulted from interaction with the VR system alone. Therefore, a redesign of the tasks so that they can provide enough opportunities for learners to demonstrate conceptual change is deemed necessary. This redesign, described in the next chapter, introduced into the system properties that aimed at capturing the moments where children could have had incorrect conceptual models of a topic, which they could then change as a result of their interaction with the system.

Figure 4.16: S3 while scaling the capital of the Ionic column.

4.3 Discussion

The study described in this chapter forms the first part in a series of studies that have set out to explore the research question -how to test whether interactivity influences learning. As such, a tenet of this first study has also been to explore the viability of Activity Theory as the main methodological and analytical approach.

Despite the small number of participants, the study succeeded in clarifying many of the technical and practical issues concerning the development of the methods and methodology for carrying out in-depth experiments with children, and a framework for analysis. At the same time, the study also highlighted some of the inadequacies of the methods used to collect and interpret the data. The participants, being young children, have difficulty in explaining their actions and, most of all, externalizing their thought process, while direct observation alone is unable to provide adequate insights into these internal thought processes. The think-aloud protocol that was used to obtain verbalisation data can be quite effective, but this largely depends on the participant's learning style, capacity to verbalise, level of extroversion, or even gender (Baauw and Markopoulos, 2004). Also, the observer had hoped to be as unobtrusive as possible but it proved difficult given that the participants had to be asked questions while interacting with the virtual environment. This is a particularly common problem, especially in VR where achieving presence is paramount to the success of an experience. Any direct method of eliciting information from the user during the experience can cause breaks in the user's sense of presence (Brogni et al., 2003; Bowman et al., 2002). Although the study of presence and its effect is not within the scope of this research (as noted in Section 1.4), breaking the illusion of presence could affect participants' engagement and interaction with the VE.

The above observation led to the conclusion that think-aloud should not be used as the only method to elicit information from young users. Consistent with the methods of Barab et al. (1999), but also with what researchers that work with children report (Markopoulos and Bekker, 2003), the need to use multiple research methods was established and reinforced. The exploratory study led to a process of identifying the methods described in Chapter 3, section 3.1, which were finally used in the main study. These include, in addition to direct observation with complete video-audio recording and the think-aloud technique, a number of different formal and informal tools for collecting the data, such as pre-post questionnaires, activity log files and informal discussions probing retrospective recall. These methods were necessary for looking through multiple data sources at what the participants did/thought so as to triangulate interpretations.

Activity Theory proved to be a useful tool for the purpose of the exploratory study. It provided the study with the analytical power to present and understand the relationships between the user, the virtual environment, and the learning objective that formed the dynamic activity system of the study. AT provides the opportunity to "see" incidents and form them into categories which reflect the different kinds of things being learnt; it served as an observational record to look for changes in behaviour that arise from contradictions such as breakdowns within the use of the VR system. The main contribution of the AT analysis has been the formulation of the understanding that learning occurs through particular types of interaction, where learning is understood as the changed intentional behaviour following failure and interaction is defined in terms of socially situated, tool-mediated activities.

Most importantly, the exploratory study clarified issues with regards to learning. The analysis illustrated that the exploratory study fell short of providing enough evidence of task learning and conceptual change. Although the construction of columns did include problem-solving activity, the intended learning goal or the inferred "learning problem", which involved understanding the differences between columns and the importance of scale and symmetry, remained unclear. Nonetheless, the incidents described above showed evidence of some kind of learning, albeit, in most cases, it was not learning that resulted from interaction with the VR system alone.

Based on the experience with this exploratory study, a number of research and design directions were identified for the main study. Since what is sought is evidence of conceptual change arising from a process of scaffolding and feedback generated by the system, the experiment tasks require re-designing to focus on achieving such change. At the same time, the design must minimise the occurrence of other kinds of learning, such as technical learning or learning as a result of external aid from the observer, and introduce into the system properties that attempt to capture the moments where users may have incorrect conceptual models of a topic, which they then change as a result of their interaction with the system. Thus, a different learning domain, that of mathematics, has been chosen in order to exploit the capabilities of the VR medium in visualising abstract and difficult conceptual learning problems and providing feedback. Hence, in order to examine "interactivity", varied levels of control over the parameters of the system were provided through an experimental VE in which children would be asked to complete constructivist tasks (such as planning the layout of a playground) that are designed as arithmetical fraction problems. Fractions were chosen as learning topics due to the difficulty that primary school students have in understanding and connecting them to real-world situations (Harel, 1991). The tasks involve modifying (resizing and placing) the various elements of the playground according to rules that require fractions calculations. The system is designed to provide intrinsic feedback to respond to the children's activity, including feedback on the rules of the task, communicated by artificial characters instead of a human observer. The experimental method includes observation, interviews and pre- and post-test questionnaires, designed in collaboration with maths teachers, for three different participant groups (two experimental groups in a VE and a non-VE group).

4.4 Summary

In this chapter, an exploratory study with three young participants was described and analysed, applying the methodological framework of Activity Theory. The study involved an experiment with column construction tasks in a virtual environment and aimed at testing out the method while attempting to examine, ultimately, the effect of interactivity on learning. Activity Theory aided in structuring the incidents caused by the users' interaction with the system and in identifying different kinds of learning (tool mastery, at a trivial level, but also the internalisation of socially-defined rules and concepts about acceptable column construction). The analysis revealed that the minimal and subtle cues that were provided by the system (e.g., the column base that could not be moved) led, in some cases (Section 4.2.1.3, Examples 3 and 4), to indications of conceptual change through the revision of the participants' personal beliefs and rules.

The shortcomings of the study informed decisions on the methodological direction that would be followed for the main study, described in the next chapters. It was decided that the main study should involve a system designed to provide more opportunities for conceptual learning, manifested through indications of conceptual change, subjects' additive knowledge, and change in behaviour. The methods for gathering the data would be enhanced to include the combination of methods presented in Chapter 3; that is, in addition to direct observation, before and after tests, and interviews probing participants' understandings. The analysis would continue exploring the Activity Theory framework in order to identify manifestations of learning through the examination of critical incidents or contradictions.

Chapter 5

The Design and Implementation of the Virtual Playground

The analysis of the exploratory study, presented in the previous chapter, revealed that conceptual learning was not clear in the specification and design of the tasks, thus making it difficult to understand whether or not the student's interactive VR experience resulted in any kind of conceptual change.

Therefore, a re-design of the interactive virtual environment in such a way that it would incorporate difficult learning tasks was considered necessary, in order to better address the research questions. The environment would have to support Bruner's constructivist perspective of children as active problem-solvers who are ready to explore "difficult" topics. Bruner illustrated his theory in the context of mathematics and social science programmes for young children: "The concept of prime numbers appears to be more readily grasped when the child, through construction, discovers that certain handfuls of beans cannot be laid out in completed rows and columns. Such quantities have either to be laid out in a single file or in an incomplete row-column design in which there is always one extra or one too few to fill the pattern. These patterns, the child learns, happen to be called prime. It is easy for the child to go from this step to the recognition that a multiple table, so called, is a record sheet of quantities in completed multiple rows and columns. Here is factoring, multiplication and primes in a construction that can be visualized." (Bruner, 1973).

The most critical and difficult step in designing the next study was to identify and construct this learning topic with which young students have difficulties. This new learning task would have to address the deficiencies that emerged from the exploratory study; in other words the learning task would have to:

1. support conceptual learning, which should be distinguished from factual learning. For example, a highly conceptual task can be to learn how to play a game of chess, since this would involve building mental models, associations, strategies, and engaging in a sophisticated level of problem solving. On the other hand, the task adopted for the exploratory studies (learning about columns through constructing them) turns out to be a weak example of a conceptual activity since it can not be easily formulated to include abstract conceptual problems that would benefit from concretization.

2. justify the use of VR. In other words, the task must be either something one could not easily do otherwise in a real-world situation, or, more reasonably, something that would be more difficult to do in a real-world situation. A virtual environment must be able to add value to the learning task in a way that could not be provided otherwise. The example of learning how to play a game of chess is an activity easily and better performed without VR. Building columns is an activity one would not and could not do in the real world but also perhaps would not need to. Resizing column parts is, in practice, a fictitious application which makes sense only if it adds to a very specific learning or training task.

3. allow for various levels of interactivity that make sense in order to complete the task. The environment should encourage the different levels of interactivity, defined in Table 2.1 and Section 2.2.1, ranging from observation and exploration with navigational ability (explorative interaction), to manipulative interaction, and even to contributive reciprocal activity. In the previous examples, the chess game task involves limited interactivity of a certain kind (mostly on a conceptual level), while the construction of columns in VR involves activity that resembles playing with construction kits, a highly engaging, manipulative, and possibly even physical activity (but not a conceptually challenging task that could provoke a change in understanding, as noted).

After considering the above requirements, it was decided that the domain of mathematics education could provide a starting point for identifying a learning task that is, at the same time, conceptually difficult, abstract enough to justify representation via a VR simulation of a real-world situation, and can allow for a kind of varied and incremental interactive treatment. Specifically, the wealth of maths education literature concerned with the problems that arise from teaching and learning ***fractions*** (and similar mathematical concepts related to rational numbers such as ratios, decimals, and proportionality) led fractions to be chosen as the underlying subject on which the design of the learning tasks for the main study would be based.

5.1 Learning Fractions

The use of fractions is prevalent in our everyday lives, even at a very early age. As children we agree to eat half our vegetables, grudgingly give up half of our cookie for a younger sibling, and even announce that we are three and a half years old (Bialystok and Codd, 2000). However, the concept of fractions and the ability to produce notational representations for fractions are among the most difficult topics of mathematics for primary school students. Fractions are conceptually complex because they involve ratio quantities, and their notations are specialised and require specific instruction. Students have difficulty recognising when two fractions are equal, putting fractions in order by size, and understanding that the symbol for a fraction represents a single number and not two numbers as its form suggests. Students also rarely have the opportunity to understand fractions before they are asked to perform arithmetical operations on them.

Fractions are being taught to primary school students in the middle years (or grades), i.e. 4th, 5th and 6th year in school, which usually means children between 7 and 11 years of age. The exact age and year in school can vary between the different school systems but, generally, students are taught the concept of "larger - smaller" in the early years (2nd and 3rd year), and then are taught "fractions" using mathematical (symbolic, numerical) representation in the middle years (year 4 and year 5). In year 6, students deal with "analogies" (i.e. a more literary representation of the same concepts), which in addition to fractions, involves ratios, decimals, and percentages. In the British school system, fractions are tested as part of Key Stage 2 Standard Assessment Tests (SATs) in Mathematics (general category of English, Maths & Science). These exams are usually taken at the age of 11.

Elementary-school children's difficulties in learning fractions and understanding their representations have been well documented (Cramer et al., 1997) and a number of projects, lesson plans, and curricula (such as the Rational Number project discussed later) have been developed, aiming at organising instruction so students can develop a deep understanding of fractions. Educational technology research projects and products have also been developed on this topic (most notably, Idit Harel's Instructional Software Design Project (Harel, 1991) and Yasmin Kafai's game development projects with fraction content (Kafai, 1995), both significant sources of information for this study).

5.1.1 The representation of fractions

Traditionally, fractions have been represented with a notation system (for example "1/3"), which essentially is an "artificial" construct used for performing arithmetical operations and learning fractions in school. Common school exam questions such as the following are indicative of this symbolic representation of fractions: "Write two fractions, each greater than 0 and less than 1, which have a difference of 3/4" or "Write two decimals, each greater than zero, which add together to make a total of 0.01". Mathematics as taught in school are deeply paper-based and symbolism such as the above involves manipulating numbers written on paper.

To facilitate understanding of fractions, educators have been using the "pie" metaphor (Niemi, 1996) to teach fractions. The "pie" metaphor (where fractions are related to pieces of a pie because they represent parts of a whole) has been the dominant metaphor for teaching fractions and a number of activities, books, and games have been developed throughout the years (Figure 5.1). This 2D pictorial representation relates somewhat to real-world situations, as do other scenarios that involve dividing pizzas or chocolate cakes. An example of a similar real-world scenario using chocolate bars is the Key Stage 2 SAT exam question that follows: "Two of the ingredients of chocolate are cocoa and sugar. In milk chocolate, 20% of the mass is cocoa, 55% is sugar. A bar of milk chocolate contains 50 grams of cocoa. How many grams of sugar does it contain?"

The problem, however, of connecting the symbols to real-world situations remains; it is often difficult for students to integrate formal instruction with their informal knowledge (Mack, 1990). Research has shown that students begin to construct a deeper understanding of fractions when these are represented in a variety of ways and when there are explicit linkages to everyday life and familiar situations involving their use. Several educators have used construction kit aids with concrete materials (i.e., manipulatives) to bridge this gap. The Rational Number project (Cramer et al., 1997) has introduced teacher lesson plans based on Lesh's translational model, shown in Figure 5.2 (left), which illustrates the five

Figure 5.1: The ubiquitous pie metaphor for representing fractions has its problems... (illustrations by Daniel Postgate, from the Murderous Maths series book *Fractions and Averages: the Mean and Vulgar Bits* by Kjartan Poskitt, Scholastic Children's Books, 2000, used here with permission).

distinct types of representing mathematical ideas for instructional purposes (Lesh et al., 1983). Lesh suggests that children learn by having opportunities to explore ideas in these different ways and by making connections between the different representations. These types of representation systems are:

(a) "scripts" in which knowledge is organised around "real world" scenarios that serve as models for interpreting and solving other kinds of problem situations;

(b) manipulative models (such as Cuisenaire rods, arithmetic blocks, fraction bars, number lines, paper folding exercises, and others) in which the "elements" in the system have little meaning per se, but the "built-in" relationships and operations fit many everyday situations;

(c) pictures which, like manipulative models, can be internalised as "images";

(d) spoken language, including specialised sub-languages (e.g., logic); and

(e) written symbols which, like spoken language, can involve specialised sentences and phrases, such as (x + 3 = 7), as well as normal English sentences and phrases.

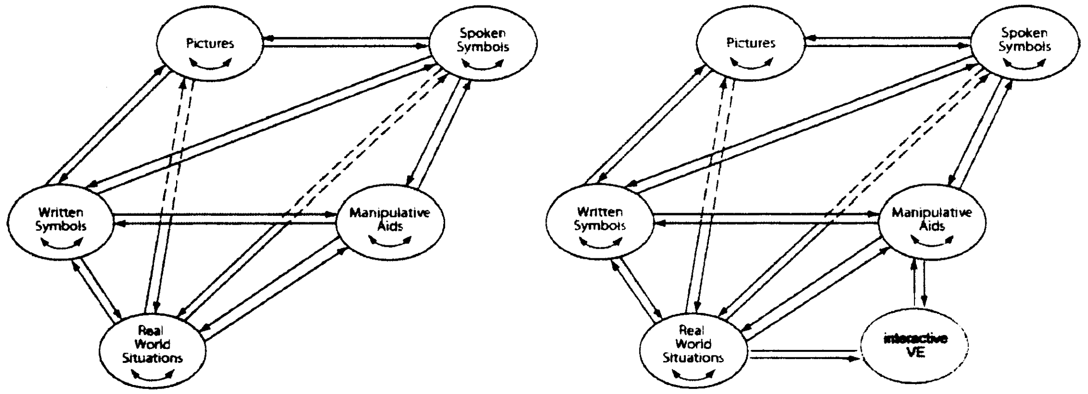

Figure 5.2: Lesh's translational model (left) illustrates the five distinct types of representing mathematical ideas (fractions) for instructional purposes. This research proposes to enhance Lesh's translational model with an immersive and interactive VR representational component (right).

Mack (1990) suggests that comparison of fractions is sometimes difficult for students who regard fractions as discrete whole numbers rather than as proportions. Similarly, Bialystok and Codd (2000) reference the work of other researchers who report that the development of children's understanding of fractions appears to parallel the development of their understanding of whole numbers, suggesting that the learning of whole numbers, and the awareness of what appears to be the same notation system interfere with the learning of fractions. For example, when comparing fractions such as $\frac{1}{3}$ and $\frac{1}{4}$, it is common for students to conclude that the fourth is larger than the third because four is a bigger number than three in the counting series. Students committing this type of error are probably applying knowledge of whole numbers to fractions. Gallistel and Gelman (1992) also confirm that, in their studies, children comparing $\frac{1}{4}$ and $\frac{1}{2}$ treated the numbers as whole quantities, therefore misjudging $\frac{1}{4}$ to be larger than $\frac{1}{2}$. They believe that this is because fractions are the first numbers that children encounter which cannot be generated as a result of counting.

Researchers suggest that teaching methods and strategies that disentangle written representation from the learning of fractions may enhance children's ability to understand fraction quantities. By relating, for example, the formal symbols to realistic situations and manipulative representations of fractional amounts, students may be less likely to consider the fourth as larger than the third. Lesh and his colleagues, from their interviews with children, noted that children constructed what they refer to as informal strategies for ordering fractions. These strategies reflect students' use of ***mental images*** of fractions to judge the fractions relative size and not taught procedures, such as least common denominators and cross-products. When comparing, for example, $\frac{2}{3}$ and $\frac{2}{6}$ (fractions with the same numerator) students can conclude that $\frac{2}{3}$ is the larger fraction because thirds are larger than sixths and two of the larger pieces must be more than two of the smaller pieces. This strategy involves understanding that an inverse relationship exists between the number of parts a unit is partitioned into and the size of the parts. These strategies closely parallel students actions with manipulatives. They are in contrast to the paper and pencil procedures, which require changing both fractions to common denominators or calculating cross-products.

Overall, the apparent complexity of a mathematical idea, as Noss (2001) argues, is often located in the representational infrastructure in which it is expressed, rather than an ontological facet of the idea itself. Thus, he talks about new ways to represent mathematical knowledge that are designed simultaneously to be learnable and rigorous. In this case, the challenge for the design of mathematical thinking tools is in designing new representational infrastructures and activity structures that facilitate mathematical expression.

Based on this view of focusing attention on the design and use of "representational infrastructures that intimately link to students' personal experience", this research argues that an immersive simulation-based environment, such as the kind that could be provided with Virtual Reality technology, can begin to formulate an additional environment of representation of deep or abstract concepts that could aid in conceptual understanding. This experiential form of representation combines the pictorial representation of fractions with a simulation of real-world situations and, in the case of interactive VR, the power of manipulative aids, albeit virtual. To illustrate this argument, Lesh's model was enhanced with an immersive VR representational component (Figure 5.2, right). It was decided that tasks that incorporate fractions problems would be designed in an immersive interactive virtual environment.

5.2 A Virtual Environment for Evaluating the Understanding of Fractions

Following the definition of the appropriate learning problem (fractions) that forms the basis for the construction of the learning tasks to be evaluated, the next task was to create the virtual environment that would incorporate these tasks in an overall activity with an engaging scenario (Roussou and Slater, 2005; Roussou et al., 2006).

The initial idea, which was developed with consultation from supportive maths and science teachers, was to create a task where the child had to build a temple by making the appropriate fractions calculations. As an idea, the construction of a temple is advantageous because it encompasses an inherently activity-rich process, following on from the exploratory study. However, as with the column construction tasks of the exploratory study, it did not provide enough opportunities for conceptual challenge and could not be easily linked to the everyday life and interests of today's children between 8 and 12 years old. Consequently, the idea of designing a playground emerged. This virtual playground had to present the child with a challenging task, which would require action on the part of the child and interaction between the child and the system. Thus, the idea of creating a playground with various elements such as swings, a slide, a roundabout, etc., which were incorrectly scaled and positioned and required the participant's physical and mental intervention to be corrected, was considered a strong and interesting challenge. In this playground scenario, the participant's task is to change the size of the area that each object occupies in the playground according to rules that are provided during the virtual experience (Figure 5.3). These rules require the participant to make fractions calculations; however the task is presented in the form of a game, with a narrative structure including engaging visuals and characters, in an attempt to disguise the maths and any potentially instructional character.

It must be noted that care was taken to avoid designing a teaching application or an instructional simulation environment, such as the virtual learning environments discussed in Section 2.3.2.3; the goal of this research from the outset has been to develop an environment that can be used to test whether interactivity in VR has an effect on children's understanding of the chosen learning domain. Consequently, the Virtual Playground (VP) that was developed is a highly interactive immersive virtual environment tailored to provide an evaluation tool for young user behaviour in VR. At the same time, however, it is an engaging environment that could easily become a learning tool. The Virtual Playground is described in the following sections, while the full scenario and final implementation are described in detail in Appendix B.

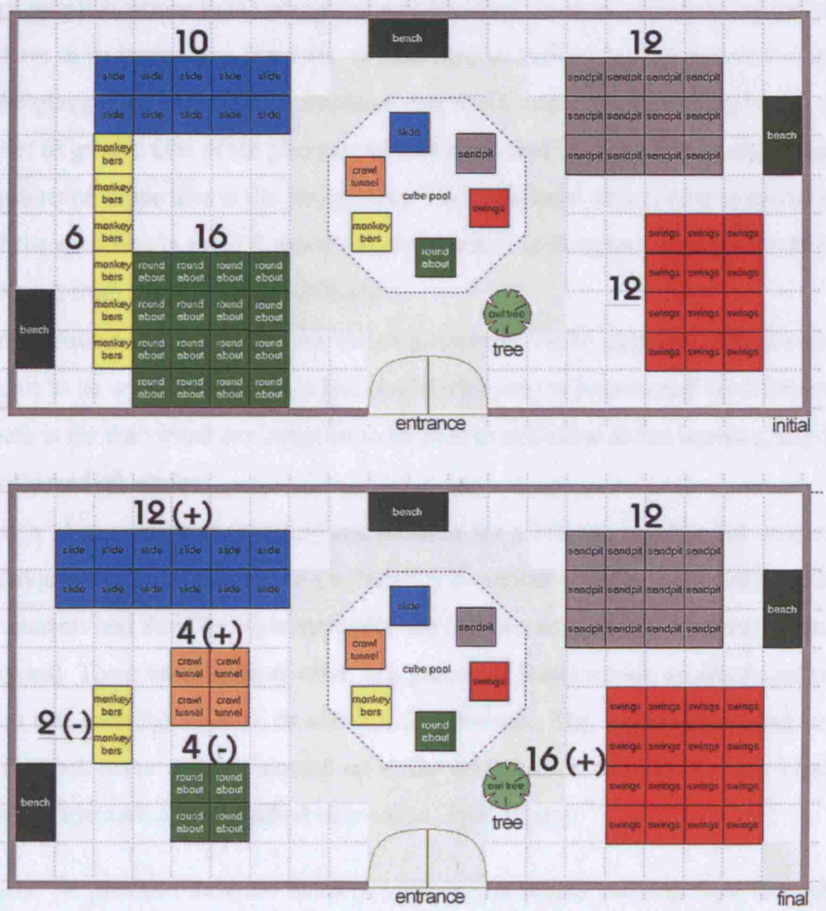

Figure 5.3: Sketches illustrating the footprint of the playground with the areas that should be covered by playground equipment; the top shows the initial coverage (with the number near each area indicating the number of ground tiles covered by blocks), while the bottom shows the coverage after the successful completion of the restructuring task (with the parenthesis next to each number indicating whether the area had to be increased or decreased).

5.2.1 Design aims

An environment such as the Virtual Playground must address the requirements listed previously and provide the opportunities to test the learning processes that may be taking place within the VE as a result of the participant's activity. Since what is sought is evidence of conceptual change arising from a process of scaffolding and feedback generated by the system, it is important to develop system properties that incorporate various levels of interactivity. Furthermore, the design must minimise the problems observed during the exploratory study, such as the occurrence of other kinds of learning like technical learning or learning as a result of external aid from the observer.

To be more specific, the design goal for the first requirement (to support conceptual learning) meant that learning tasks should be designed within the general domain of fractions, which require specific conceptual activity on the part of the participant. In the Virtual Playground, different exercises were included, from simple fractions to the comparison of fractions, in an attempt to bring forward problems that students have in understanding fractions, as identified in Section 5.1. Moreover, the overall task of redesigning the playground must obey a fractions rule itself, requiring, according to the scenario, that the total number of ground tiles of the playground that is covered by playground equipment must not be more than a quarter of all the tiles in the playground. The participant may choose to complete only some and not all of the exercises in the VP, since the environment is designed to accommodate a variety of fractions problems, from simple to more difficult.

The second requirement (to justify the use of immersive VR by applying it to content that would be more difficult to do or to represent in a real-world situation) is approached on different levels. The design goal here is for the virtual environment to be able to add value to the learning task in a way that could not be achieved otherwise.

Designing a playground is most likely not possible for a child in real life but an environment for designing a playground can, of course, be provided by a number of tools, both computerised (2D multimedia environments and SimCity-style microworlds) and non computerised (construction kits or plain paper and crayons). These environments offer, to a greater or lesser extent, an abstracted representation of the situation that suits the medium in which it is delivered. The added value of an immersive VR environment for such cases can be summed up as the combination of more realistic representation, a higher level of engagement, and embodied interaction. Specifically,

- immersive VR provides different fields of view or viewpoints, ranging from faithful simulations of the real world to metaphorical representations that aim at bringing to students concepts and principles that normally lie outside the reach of direct sensory experience (Winn, 2003). In the design of the VP, the participant assumes her unique first-person perspective through head and hand tracking, but also through the different views programmed into the environment: a ground view, which simulates a human-scaled environment that surrounds the user (Figure 5.4), and a top-down or birds-eye view, which replicates the perspective that architects use when draughting the layout of a space (see Figure 5.8 in Appendix B). In a non-computerised environment (using paper, clay, bricks, manipulatives, etc.), a ground view of a playground in human scale and in correct perspective is rather unlikely and difficult to produce. In VR, correct perspective is achieved by rendering the world according to the user's head position and orientation. A top-down view, on the other hand, is easier to reproduce in different media; yet this kind of view is an abstraction of a space, similar to that of a map, and certainly not the view one would encounter in a real life situation. A top-down view was -inevitably- the only way to represent the playground in the case of the non-VR group of the main study, where LEGO bricks were used (see Figure 6.4; also described in Chapter 6).

- immersive VR is inherently engaging and attractive. One of the initial design goals has been to connect the idea of re-designing a new playground to a potentially realistic situation which the children could engage in and identify with. Immersive VR plays an important motivational role in this direction. The novelty of the technology as well as the engaging design of the virtual environment can capture a learner's interest, which in turn can promote conditions for effective learning (Bricken, 1991).

- immersive VR provides a sense of embodiment, which contributes to the degree of interaction and the feeling of immanent presence, compared to interacting with more abstract representations such as interface metaphors that conventional computer interfaces provide (Dourish, 2001). In other words, the kinds of interactions experienced in virtual reality environments fit more naturally with the absorbed and unreflective manner in which we act and interact with the everyday world (Rogers et al., 2002). In the VR system used for this research (see section 3.1.3), the participant can use her whole body to bend, reach, or stretch in the same way as in the real world -with the exception of walking for more than a few steps and picking objects by using both hands to grab them. Experimental studies have shown a positive effect of body movement and kinaesthesis on presence; in other words, that the high match between proprioception and sensory data afforded by an immersive VE can enhance the feeling of presence (Slater et al., 1998).


Figure 5.4: A photograph of one of the real playgrounds (in Vienna, Austria) used to model the elements of the virtual playground (left); The models created for the virtual playground, experienced from a similar ground-view perspective as in the real playground (right).

Finally, the third design requirement, to encourage and support different levels of interactivity, from "low" interactivity (navigation and exploration of the environment) to direct manipulation and contributive interactivity, is at the core of this research and thus will be analysed further in the next section.

In addition to the above design requirements concerning the tasks, two main principles were carefully taken into account throughout the overall design and development of the environment, in order to capture and maintain the participant's attention within the virtual environment: usability and engagement. Thus, strategies have been drawn from taxonomies of motivation for learning, from the entertainment practitioners (Schell, 2003), and from researchers that have been designing interactive environments for and with children. Malone and Lepper have identified a number of reasons that determine engagement in computer games, most notably the triptych of challenge, curiosity, and fantasy (Malone and Lepper, 1987). These can be achieved through clearly articulated goals, variable levels of difficulty, and cognitively challenging as well as unpredictable elements. Other researchers, such as Druin (1999), concur with these findings and report that children want interfaces that they can easily control but that, at the same time, "respect them" (in other words, are not too simple). The instructions should be designed to be appropriate for the intended age, easy to understand and remember, supportive rather than distracting, and should allow the children to control the amount of information that they get (Hanna et al., 1997). In a few words, Hanna et al. (1999) suggest that digital environments for children must be "inherently interesting, have expanding complexity and should include reward activity". Another design suggestion refers to creating self-revealing environments (Kahn, 1999), in other words, environments designed so that an inquisitive explorer can discover what objects exist and how they behave. Even though every action in the VP was designed to support the fundamental purpose of the system, i.e. to provide system feedback and observe if this feedback affected the children's decisions in completing the tasks, the elements in the playground afforded and supported inquisitive activity: most objects could be moved or would respond to user input either visually or through sound. Hence, in the VP, goal-setting is explicit and the means to achieve it are given in an understandable manner, through explanation and example. Additionally, the learning tasks are presented in a way that triggers the intrinsic need to play a game, appearing as an inherent part of the game itself (Ritterfeld et al., 2004). At the same time, the VE was kept as "uncluttered" as possible in order avoid distraction and allow the child to focus on the main activity.

Overall, the aim was to include as many as possible of the suggestions that proponents of constructivism, such as Jonassen (1988) and others, have made regarding the design of instruction (see also Section 2.1.2), as well as the tricks and methods used by museum practitioners and interaction designers within the entertainment sector, as presented in the examples of Chapter 2. These methods, combined with previous experience in developing child-centred virtual worlds (Roussos, 1997; Roussou, 2004, 2006), resulted in the virtual environment described below.

5.2.2 Description of the virtual environment

Guided by the above design principles, an interactive virtual reality environment was created specifically for projection-based immersive displays such as the CAVE. The design for this specific display medium entailed careful attention to the mapping of the scale of a physical environment to the virtual representation. This means that the scale of the objects in the virtual environment was adjusted to "look right" to the average 10 year old, i.e. to a person with an average height of 120cm. Since the Virtual Playground was targeted to children between 8 and 12 years of age, the introduction to the tasks and overall presentation followed a scenario-based approach with a game-like narrative, plot, and characters (Figure 5.5). The goal was to connect the idea of re-designing a new playground to a potentially realistic situation which the children could identify with, without connecting it to a formal instructional process or a standardised testing scheme. In other words, the design was meant to contribute to the creation of a meaningful context where the tasks are embedded in a storyline.

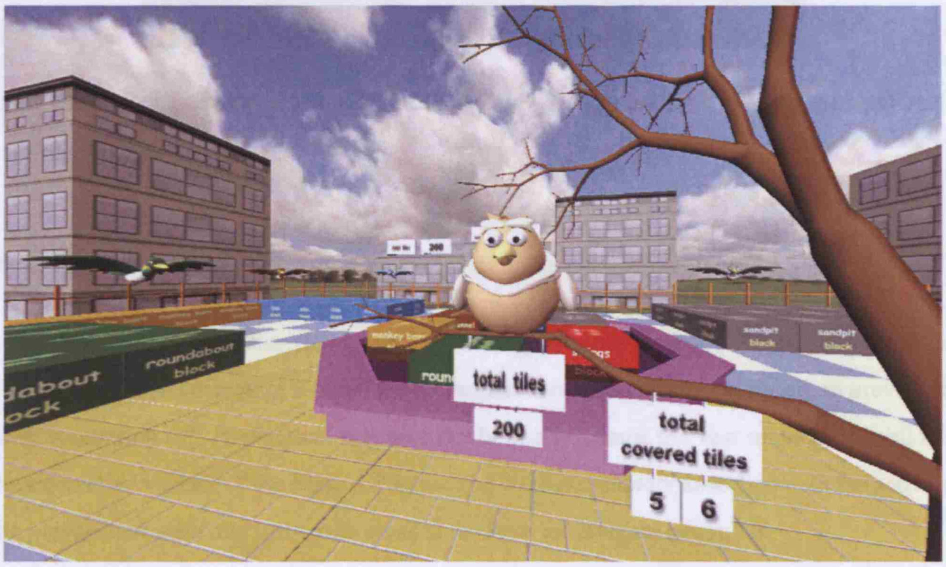

Figure 5.5: An overall view of the Virtual Playground environment with coloured blocks representing the areas where play equipment will be placed once corrected by the participant.

The virtual environment includes areas that remain unchanged and areas/objects that can be modified by the participant. The main part of the playground that remains fixed is the ground. The ground is a rectangular area divided in equal visible tiles that were designed to represent a unit of 1 metre each. The total area of the playground is 10x20, meaning ten tiles in width (equivalent to 10 metres) and 20 tiles in length (equivalent to 20 metres). In other words, the virtual playground is a simulation of an area of 10m x 20m in human scale. These tiles are clearly visible on the ground surface of the virtual environment in the form of a blue and white checkerboard. The function of the ground is central to the learning tasks designed around fractions. The ground is used as the unit base, on which blocks are placed to designate areas; in other words, the ground tiles provide the reference for every other object created in the environment. However, when this initial design was implemented, the tile size of one square metre seemed too large to be practical, especially for children who would have difficulty in manipulating the virtual objects and navigating larger distances. Thus everything was halved (i.e. 1 unit became 50cm, one tile 50cm by 50cm and each block 0.5 cubic metres).

Figure 5.6: The owl character is the "spirit" of the Virtual Playground, introducing the story and overall goal to the participant.

Other elements in the playground areas that remain unchanged include:

- a picketed fence surrounding the playground to keep the activity space focussed. Beyond the fence, a transparent wall (detecting wall collision) was added around the playground, to prevent the child from wandering off. In practice, this was rarely needed, since the vast majority of children using the interactive version of the Virtual Playground were completely absorbed with the activity within the playground area, and did not express an interest to navigate beyond it.
- background scenery, such as buildings, trees, grass, the sky and the horizon. As these were not important to the learning task, they were designed to enhance the aesthetics and believability of the VE without attracting attention. An entrance gate to the playground was included. The gate opened every time the participant approached it and closed shortly after.
- other elements in the playground that cannot be altered, such as three benches and a tree by the entrance. The tree is home to the main character of the playground, an owl. The owl introduces the overall scenario and initial rules to the participant. When the owl is talking, her eyebrows and lips are animated, while her eyelids open and close, making the character very engaging and believable (see Figure 5.6).

The dynamic parts of the VP are the models that can be manipulated or that are of importance to the interactive part of the experience. These include:

- six different playground objects or play equipment (swings, a slide, a roundabout, monkey bars, a crawl tunnel, and a sandpit), and six differently coloured sets of blocks representing the area that each one of the above objects covers in the playground, as shown in Table 5.1. Written on each block is the name of the play element it represents.

Figure 5.7: A virtual "talking bird" floats over each area of the playground that needs to be changed, speaking out the rule for that area.

sandpit	grey blocks
slide	blue blocks
crawl tunnel	orange blocks
roundabout	green blocks
monkey bars	yellow blocks
swings	red blocks

Table 5.1: Playground elements and the colours used to represent them in the VE

- a block pool in the centre of the playground, where the extra blocks are located (and "stored") for the participant to pick from and/or return to.
- six models of birds in different colours, corresponding to the six different areas of the playground that need to be changed. Each bird "floats" above the object it corresponds to and provides instructions related to the exercise or task that the participant has to perform with that object (Figure 5.7).
- information signs: a sign (hanging from the tree as well as mounted on a billboard on the top of a building) displaying the number 200, which is the total number of tiles that make up the playground (Figure 5.5). Also a separate sign structure with signs that act as counters (also hanging from the tree and mounted as a separate billboard on a building) and which change dynamically to display the number of tiles that are covered by an object at any given point. The counters are updated every time a block is added or removed from the playground grid (Figure 5.5). The signs were placed apart in horizontal (one next to other) instead of vertical (one above the other) order so as to not allude visually to the symbolic form of a fraction, i.e. $\frac{x}{y}$, where x is the number of covered tiles and y is 200, the total number of tiles of the playground.

The participant's task involves modifying the size, shape and maybe position of the area that each object covers, according to rules provided for each area (see Figure 5.3 for sketches illustrating the "before", or wrong, and an "after", or correct, schematic view of the playground). This can be done by adding, removing, and moving around the appropriately coloured blocks. There are two different modes to support activity and two different views for reviewing the playground. The modes are:

- **construction mode**. This is the default mode in which the participant works to change the size and position of the playground elements. In this mode, the area that each object covers in the virtual playground is represented by the set of coloured cubes/blocks (with colours as shown in Table 5.1), where each block is as big as one tile. The extra blocks are stored in a central location, a "block pool", where blocks that need to be added to the playground are picked from and blocks that need to be removed are dropped in.

- **playground mode**. This is the mode in which the 3D models of the six playground objects are displayed when their size and position are corrected. Only the corrected models, i.e. the models that cover an area which conforms to the rules of the game, are displayed in playground mode. This means that, to start with, no models are displayed in playground mode, whereas when the task is finished, all models can be seen.

The participant is able to switch modes at any time throughout the activity, i.e. to switch between blocks (construction mode) and models (playground mode), in order to review the changes made to each area and see if they were correct.

The views of the virtual playground are:

- **ground view**. This is the default view where all exploration via navigation and manipulation activity is carried out.

- **top-down view**. This is a birds-eye view of the playground, similar to a footprint (Figure 5.8). It was added to the design to provide an alternative view, helpful for gaining an overview and for counting blocks, and thus minimising the need to navigate.

A typical sequence of events and activity in the virtual playground, as well as a brief description of the tasks are presented below.

5.2.2.1 Introduction

When the Virtual Playground program starts the participant is automatically moved on a predefined path through the gates of the playground and positioned in front of the tree. At this point, navigation is disabled and the initial state of the VP is in "playground mode", displaying models of the playground elements. However, the models of the elements that must be changed later appear distorted and grey, to emphasise that they are not in the correct size and position. An owl character seated on a tree branch at eye level (Figure 5.6) introduces the story and the overall goal (for a detailed presentation of the entire script, see Appendix B.2).

The owl explains that the overall task is to modify the size of each area/object by adding or removing blocks of the colour that represents it. The participant is guided by the owl to practice the use of the

Figure 5.8: A top-down view of the playground, as seen when clicking on the blue button.

buttons on the interaction device (called "magic wand"), which includes a joystick for navigating the environment and colour-coded buttons (Figure 3.1). In addition to using it for navigation, the joystick is also a big button that can be pressed to select objects, which includes picking and placing blocks or making the birds "talk". To add a block, the participant will pick it from the central block pool and place it on the intended tile. To remove a block the participant will pick it from its location and drop it in the pool. The red button is used to toggle between "construction mode" (in which construction takes place) and "playground mode" (in which solutions can be reviewed) and the blue button is used to toggle between the default ground view and the top-down view of the playground (Figure 5.9).

During the instructions, the participant is asked to switch the playground to "construction mode". The playground remains in this mode until the participant has clicked on the red button to switch to playground mode. However, only the areas that have been constructed correctly in construction mode will be replaced with the appropriate model (scaled accordingly) in playground mode. The areas that have not been changed or have not been completed correctly will not be replaced by models (i.e. will remain visible as blocks).

5.2.2.2 Tasks

The participant sees a different configuration of the playground at the beginning of the experience and the overall task, as explained, will be to correct the area sizes and positions by moving the appropriate blocks around, according to the rules provided by each of the birds that float above each area of the playground. The only blocks that cannot be moved are the ones representing the sandpit, since the sandpit is purposefully the only correct model, used as a reference for the fractions calculations on other areas. Therefore, there are five tasks that expect activity on behalf of the participant, and can be performed in any sequence she chooses. These tasks and their mappings to fractions problems are:

Sandpit task. As mentioned, nothing needs to be done to the sandpit area. The grey bird floating over one of its four corners states that the sandpit is the only model in the playground that is correctly sized and positioned, so it does not need to be changed. The sandpit takes up twelve tiles, or 12/200 of

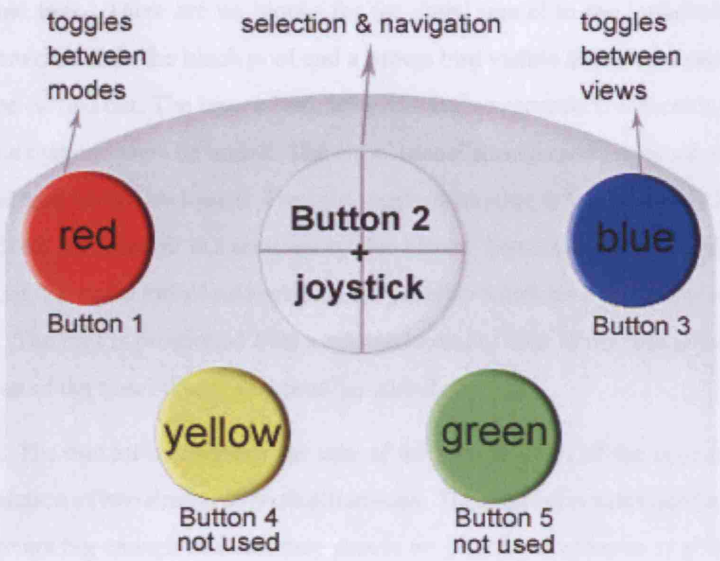

Figure 5.9: The front (top) three buttons of the hand-held interaction device are used for interaction in the Virtual Playground: the middle button, which couples as joystick, is used to select objects (pick and let go blocks and trigger birds to talk); the left button (red button) is used to change modes; and the right button (blue) is used to change views.

the total playground area, and is used to calculate the final number of blocks needed by the monkey bars and the crawl tunnel.

Roundabout task. The roundabout initially covers sixteen tiles, or 16/200 of the total playground area -a large part of the playground considering the size of the other areas. It is thus obvious that the area must be reduced. According to the green bird, blocks must be removed from the roundabout and only one quarter of what it covers now must be left on the ground, meaning four blocks left on the ground. The bird adds that the resulting area must have the shape of a square. In the case of the roundabout, the positioning is important -it must not be too close to the fence or the footpath and it should leave enough space for the crawl tunnel and the monkey bars to fit as well.

Monkey Bars task. The monkey bars are initially a long strip of six blocks near the left side of the playground. Here the participant learns from the yellow bird that blocks must be removed to make the monkey bars smaller. The number of blocks to be removed must be decided by looking at another area, the area of the sandpit, which covers 12 tiles, and finding how much one sixth of that area is. This number will be the final number of blocks that should be left on the playground for the monkey bars.

Slide task. For the slide, the initial area covered by blocks is ten tiles or 10/200 of the total playground area. The tiles form two rows of five blocks each, placed in one corner of the playground, only one row away from the fence on the long side of the area. The rule is to increase the slide by one fifth of the area that it currently covers. Thus, the correct solution is to add two blocks, making the area two rows of six blocks. The two blocks could be added on either side of the two rows; however, one tile on the side near the pool is the footpath, on which the system will not allow blocks to be placed.

Crawl Tunnel task. There are no blocks for the crawl tunnel in the initial configuration of the playground. A brown block in the block pool and a brown bird visible in the environment are signs that there is a task to be carried out. The brown bird, when clicked on, reveals that there is no crawl tunnel in the playground and that one must be added. The crawl tunnel should cover as much area as one third of the sandpit and the area should be square. The bird suggests looking at the sandpit to find out how many blocks must be added. The sandpit is a constant twelve blocks, hence the number four is the answer. As with the roundabout, the crawl tunnel rule restricts the possible solutions by pointing out that the number must be a square. The bird is positioned over a relatively empty area of the playground thus indicating the general location of the crawl tunnel that must be added.

Swings task. The rule for redesigning the area of the swings is one of the more complex ones, as it requires the comparison of two similar sounding fractions. The red bird communicates the rule by noting that the swings are not big enough and that they should be given as much area as possible. The options are to make the area bigger by one third of their current area or bigger by one fourth, whichever covers more ground. As the swings area is initially twelve blocks, the choice of one third is the correct choice, resulting in four blocks. The position of the swings is rather tight, between the fence on two sides and the sandpit on the third, so the participant has quite a few restrictions with regards to placement of the additional blocks (and perhaps an extra hint on how many will be added).

In the end, when the above tasks are performed correctly, the final covered tile count should add up to a quarter of the total number of tiles making up the ground of the playground. The number 50 will be displayed on the signs confirming this. This general rule is an additional source of information, which could be used by the participant, especially if there are problems completing the final task. The task, initial state, rule for change, required change, and final state for each area are summarised in Figure 5.10.

5.2.2.3 Closure

The tasks have been designed with a reward structure in mind. Hence, when the participant completes each task, the correct model of the play object is immediately displayed. As soon as the last task is completed, children's voices cheering and clapping sounds are heard. Moreover, the pool in the centre of the space (which by now will be emptied of blocks) acquires an impressive water fountain, programmed with the use of particle systems. At the same time, the roundabout starts spinning and the swings start swinging (Figure 5.11). Thus at the end of mastering the challenging problems, the playground "comes alive" with a cheerful ending that provides a closure to the task and enhances the participant's sense of accomplishment, an important element when it comes to working with children. In fact, these features were added to the environment after taking into account the suggestions of one of the pilot study participants who, after completing her task, was disappointed and felt that "something was missing at the end".

For detailed information on the specific elements of the design and implementation of the Virtual Playground environment for an immersive VR system, see Appendix B.

Task area	Initial area covered	Rule for change	Change (0, +, -)	Final area covered
sandpit	**12** tiles or 12/200 of total playground area	The sandpit is correct –it is the only thing in the playground that does not need to be changed.	**0**	**12** tiles
slide	**10** tiles or 10/200 of total playground area.	The slide is smaller than it should be. Its area must be increased by 1/5 of the area it covers now.	+	**12** tiles
crawl tunnel	**0** tiles	A crawl tunnel must be added. The crawl tunnel should be a square and should cover as much as 1/3 of the area of the sandpit.	+	**4** tiles
roundabout	**16** tiles or 16/200 of total playground area.	The area for the roundabout is too big and must be reduced to 1/4 of the area it covers now. The area must remain square.	-	**4** tiles
monkey bars	**6** tiles or 6/200 of total playground area.	The monkey bars are too long and should be changed to cover only as much as 1/6 of the area of the sandpit.	-	**2** tiles
swings	**12** tiles or 12/200 of total playground area.	The swings are not big enough and we want to give them as much area as possible. We can make them bigger by 1/3 of their current area or bigger by 1/4, whichever covers more ground.	+	**16** tiles
general	Overall, the covered area is a total of **56** tiles (or 56/200 of total playground area).	Overall, the covered area must not exceed a quarter of the total area of the playground.	-	**50** tiles

Figure 5.10: A summary of the tasks listing the initial state, rule for change, required change, and final state for each area of the Virtual Playground.

5.2.3 Interactivity and system feedback

The participant's main goal within the Virtual Playground is to redesign the space so as to create a correct playground. As with the tasks of the exploratory study, the tasks that need to be carried out within the Virtual Playground can be structured according to the multi-level hierarchical model of Activity Theory, where the general activity consists of actions, which in turn consist of operations (see Table 5.2).

Additionally, the participant's interaction in the VP has been considered both on a physical and on a cognitive level. Drawing from the definition of interactivity presented in Section 2.2.1, in particular Pares and Pares' classification of explorative, manipulative, and contributive forms of interaction (Pares and Pares, 2001), an effort was made to include elements from all three of these forms of interaction in the environment of the Virtual Playground.

Explorative interaction is supported through the ability to navigate freely in the environment. In this case, the participant has complete freedom to move around the virtual environment by using the joystick on her hand-held wand. This kind of interaction is regarded as the lowest possible form of interactivity in the VP.

Manipulative interaction is supported by the ability to pick and place elements in the environment or switch points of view to review things. In the VP, this kind of interaction is the main form of activity on an operational level, yet it is still somewhat limited since more elaborate forms of manipulation (for example, scaling or object deformations) are not supported.

Figure 5.11: When all tasks have been completed successfully, the block pool turns into a water fountain and playground elements such as the swings and roundabout become animated.

Finally, *contributive interaction*, which refers to the most involved form of interaction, is the ability to alter the system itself. The VP supports contributive interaction, since the participant is able to change the environment as a whole (i.e. the playground being different when the participant comes out of it from when she went in). What is of interest to this research, however, is contributive interaction that takes place on a conceptual level; in other words, interaction that leads to conceptual change or contributes towards a change of the child's mental models.

In order to support this kind of interaction, rules, constraints, and a related system feedback mechanism have been designed into the VP, aiming at establishing reciprocal activity between the participant and the system. A central goal of the system feedback is to provide constraints on where the blocks can be placed. The main purpose is to constrain participants' actions in such a way as to provide conceptual conflicts (or contradictions, to use the Activity Theory terminology), especially for students that have been struggling with the content in the first place. Another goal of the system feedback has been to minimise external (human) instruction or intervention, e.g. feedback by the observer. As noted in the conclusions of the exploratory study (Chapter 4), the extrinsic feedback which was provided to the participant by the observer, altered, in some cases, the participant's behaviour. The goal in designing interactivity for the VP has been to omit the intervention of the observer, so the instructions given to the child and the rules are communicated by the virtual characters (the owl and the birds).

To meet these goals, system feedback in the VP has been programmed to *inform*, *confirm*, or *react* to incorrect participant activity by *prompting* for further action. For example, feedback to inform is presented to the child by the virtual owl, while the rule for each area is provided by a same-coloured bird, which floats over that area and talks to the participant when clicked upon. Confirmation feedback is provided through sound effects that confirm each action and through verbal statements such as "This is too close to the fence". The system provides reactive feedback concerning placement of the blocks onto the playground tiles since not all tiles of the playground are available for placing blocks on. For

AT structure	Task	Fraction calculations
Activity level	create a correct playground	Yes
Action level	change size (area) of playground equipment	Yes
	change position of playground equipment (move area)	No
	compare relative size of objects	Yes
Operations level	push on joystick and point to navigate	N/A
	point to a block and press wand button to pick	N/A
	move wand and press button to drop block in pool	N/A
	move wand and press button to place block on tile	N/A
	press button to switch btw. modes	N/A
	press button to switch btw. ground and top-down view	N/A
	look at number of covered tiles on signs	Yes
	count the number of blocks in a specific area	Yes
	count the number of blocks in other areas	Yes
	compare areas	Yes

Table 5.2: Virtual Playground tasks structured according to the Activity Theory hierarchy.

example, if the tile where a block is to be placed is adjacent to the playground fence or a bench, or is any one of the other "forbidden" tiles (i.e. footpath tile, entrance gate tile, tiles around the pool), then the block cannot be placed and a different kind of system feedback sound for each case will be heard. Additionally, each block, when placed on a tile on the grid, is checked against every adjacent tile on all four sides. If any of the adjacent tiles are of the same type (i.e. of the same colour), then the block can be placed. If not, then the system does not allow its placement and responds to the participant with appropriate audio feedback. For usability reasons, each block, when placed on the grid, adjusts and snaps into place in order to facilitate the child's physical task and leave room for more concentration on the conceptual task.

In some cases, an incorrect action produces no change in the environment. In most cases, however, visual and audio cues enhance the constraints and restrictions designed into the environment. In other words, if, for example, the participant, after performing an exercise to restructure an area, clicked on the mode change button (red button) to see the blocks switch into models of the play equipment (an indication that the task had been performed successfully) but the switch did not produce the expected result (the blocks remained and no model appeared), this constituted a simple form of visual feedback. This was then enhanced with the use of sound effects.

In a virtual environment, system feedback can be delivered in a multi-modal fashion, taking advantage of the different human senses (visual, aural, haptic, olfactory, etc.) and the appropriate interfaces. In

user action	interaction	visual fdbck	audio fdbck
move around in the environment	explorative	Yes (mid)	No
listen to rules	explorative	Yes (mid)	Yes (high)
repeat rules by clicking on a bird	explorative	No	Yes (high)
pick block	manipulative	Yes (high)	Yes (high)
place block	manipulative	Yes (high)	Yes (high)
forbid block next to block of other colour	manipulative	Yes (low)	Yes (high)
forbid block to be placed on footpath	manipulative	Yes (low)	Yes (high)
forbid block to be placed near bench	manipulative	Yes (low)	Yes (high)
forbid block to be placed near entrance	manipulative	Yes (low)	Yes (high)
switch to "construction mode"	explorative	Yes (high)	Yes (high)
switch to "top-down view"	explorative	Yes (high)	Yes (high)

Table 5.3: List of different user actions and corresponding form of system feedback, as implemented in the Virtual Playground.

the VP, the system feedback was chosen to be provided through the two most common sensory modalities, visuals and audio. It thus provides both direct and implicit visual and audio feedback to respond to the children's activity. Audio feedback has been given equal emphasis and ranges from simple sound effect feedback to more sophisticated verbal feedback. Verbal feedback has been designed to either prompt children to reflect on their action or prompt them to act. An audio example of prompting children to reflect could be the following: "If you are still seeing blocks rather than play equipment, then there is something wrong. Can you figure out what is wrong?" A prompt to action may be slightly different: "If you are still seeing blocks rather than play equipment, then there is something wrong. Can you move blocks around to figure out what is wrong?" The design of such prompting techniques was inspired by Davis' work on the use of directed prompts and generic 'stop and think' prompts to scaffold students' reflection for science learning (Davis, 1998). For the VP, it was decided that very simple 'stop and think' prompts would be used, such as "Are you sure this is the correct place?"

Examples of different user actions and their corresponding form of system feedback, as implemented in the VP, are listed in Table 5.3.

5.2.4 Recording and playing back activity in the virtual environment

In the process of designing the Virtual Playground and designing the study that would require participants to interact with it, a version of the same virtual environment that was not interactive was considered and implemented. This non-interactive virtual environment would have to *not* allow the user to explore freely via navigation, manipulate objects or receive system feedback through the feedback mechanisms described earlier. Rather, the user would be able to observe the activity as in passively watching an "immersive video" or participating as a visitor in a guided tour. An implicit guided tour metaphor was considered the most appropriate way to achieve a passive yet immersed experience. In order to construct this, the interactive VR program was enhanced with a feature to allow recording of an expert person's activity in the VE, including all movement, manipulation and feedback received by the person from the system. This set of events was recorded and stored into a file in real time. The program (or, to be precise, a slightly different version of it) could then be executed again, this time reading the file of events and playing it back in the virtual environment. This playback or "reenactment" of events was executed by a virtual character or avatar, which was created specifically for this purpose (Figure 5.12).

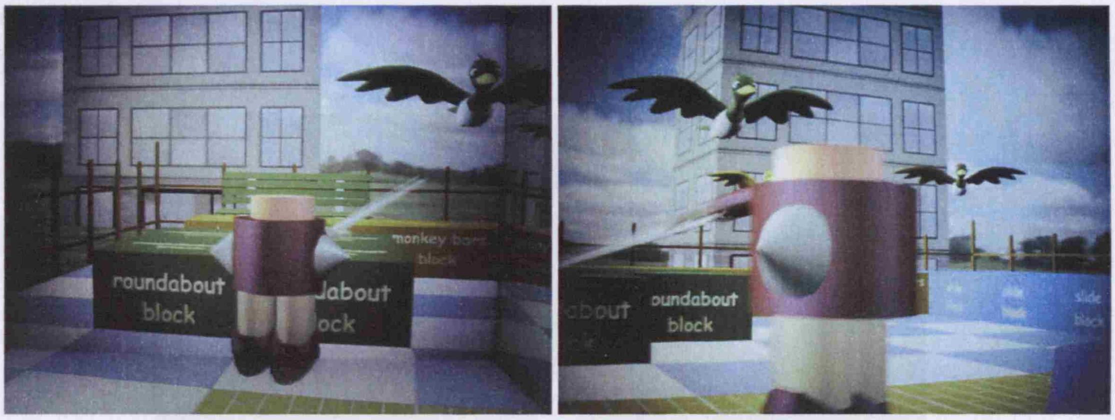

Figure 5.12: The robot interacting with the Virtual Playground on a pre-recorded script.

The initial scenario with the owl introducing the user to the construction activity required within the playground was played back just as in the interactive VR condition. However, the demonstration of the roles of the buttons (the red button to switch to construction mode and the blue button to view the playground from above) that required the user to try them out by pressing on them, was performed automatically. As soon as the owl completed narrating the introduction, the robot appeared to play back the recorded movement and activity. For the purposes of this research, the choice of events and activity that were recorded followed a long testing process based on observing typical participant interaction with the interactive version of the Virtual Playground during the pilot study, described in Section 6.1.5. As a result, the recorded sequence was timed to include use of all the features provided by the interactive VE, the successful completion of all the tasks, and the necessary pauses within 27 minutes. Appendix B.4 includes further information on the implementation of this version of the VP.

The purpose of this environment was to enable the comparison between an interactive -plus immersive- virtual experience and a non-interactive -albeit still immersive- virtual experience. This method preserved the exact same environment with all its functionality and ensured that the only difference between the two environments would be the ability to interact with them. Researchers investigating the effect of VR in training users to perform an assembly task have used a similar approach to compare an interactive VR training package with a passive video training package, where the video training was in fact a passive (animated) version of the same interactive VR training environment (Eastgate, 2001).

This version of the Virtual Playground, i.e. the version where prerecorded activity in the VE was played back, was used for the passive VR condition of the main study, described in the next chapter (Section 6.1.1).

5.3 The LEGO Playground

In addition to the virtual playground, in both its interactive and passive form, a physical model of the playground was created using LEGO bricks (Figure 5.13). The LEGO playground corresponds to the top-down representation of the virtual playground as seen in construction mode, where the virtual blocks are 4x4 plastic LEGO bricks and the tiles 4x4 light grey and white LEGO plates. This model was made to support the non-VR condition of the main study. Further information on this activity can be found in Chapter 6.

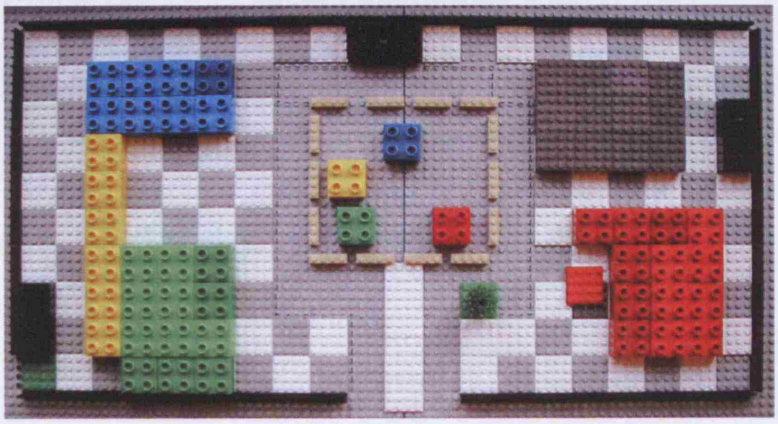

Figure 5.13: A LEGO playground was created, representing the playground areas with coloured bricks and the tiles with grey and white plates. This corresponded to the top-down view of the Virtual Playground when in "construction mode" (block mode).

5.4 Summary

This chapter described the development of the virtual environment that was used as the basis for the main experimental study, which is presented in the next chapter. This environment was designed to address the shortcomings of the exploratory study carried out in the earlier phases of this research.

Specifically, the earlier exploratory experiment, described in Chapter 4, was carried out in order to explore the research question, to identify the elements that form the relationship between interactivity and learning, and to prove the viability of the first methodological and analytical approach. The analysis of the exploratory experiment revealed a number of shortcomings, one of which was the inadequacy of the learning task -constructing columns- in triggering opportunities for conceptual change. This led to the adoption of a learning task with which young students have deep conceptual difficulties, in this case arithmetical fractions. Fractions were considered appropriate for the follow up study because they addressed three main directions that emerged as issues in the exploratory study. Firstly, the study of fractions addresses the requirement that this research established at the outset, namely the examination of conceptual learning, since fraction exercises provide the opportunity to form learning tasks that relate to abstract conceptual problems (Section 5.1). Secondly, a VR representation of fraction problems can form an ideal alternative representation, which combines the conventional pictorial representation with the possibility of manipulation and a real-world context. Finally, a VE that incorporates fractions exercises can provide a number of opportunities for reciprocal activity, both conceptual and physical.

These needs guided the design and implementation of the Virtual Playground (Section 5.2), an environment in which children redesign the landscape of a playground by performing tasks that require making fractions calculations. Two versions of the Virtual Playground were programmed: one version included a number of visual and audio feedback elements to correspond to the various levels of interactivity explored within this research. The second version was a form of passive "immersive video", where a virtual robot performed the tasks within the playground, based on a prerecorded sequence of events (Section 5.2.4).

The two virtual reality renditions of the playground, as well as a physical model created with LEGO bricks (Section 5.3), were used to perform the main evaluation study, described in the next chapter.

Chapter 6

Main Study

As already described throughout this thesis, the purpose of this research is to evaluate the value of user interaction in interactive virtual learning environments. Specifically, the goal is to evaluate if children learn better by interacting in (i.e. exploring, acting upon, and reacting to) an immersive virtual environment; in particular, if their interaction enhances conceptual learning of a subject matter. The Virtual Playground environment, described in Chapter 5, was designed as the vehicle for the evaluation of the research questions. Centred around this environment, a large-scale experimental study was planned and carried out. The study, which was informed by the observations of the exploratory study (Chapter 4) involved an experiment where children were engaged in (re)designing a playground. The design task required that the children make mental calculations in the form of fractions operations in order to meet the design parameters given by the system and, consequently, to complete the task.

The focus of this study has been to capture behavioural and conceptual change, shown to be triggered by interactive activity in the virtual environment, and compare this activity with a passive VE and with a non-interactive physical representation of a playground using LEGO bricks.

This chapter includes a detailed description of the main evaluation study that forms the crux of this research and concludes with a presentation of the pilot study that was carried out to test the experimental design and the environments used for the main experiment.

6.1 Experimental Design

The study was designed to address the research questions through a number of conditions and data collection methods. Different conditions were conceptualised in a between-groups design, attempting to cover the different combinations of activity, interactivity and immersion (see Table 6.1). Then, multiple different methods of testing were designed, ranging from the quantifiable pre- and post- questionnaires to the more qualitative observations and informal interviews.

Initially, the design of the main study was based on dividing participants into groups according to factors that could have an influence on their performance. An attempt was made to 'match' as many variables as possible across the conditions. Apart from age and gender, other variables under consideration for selecting and grouping participants for the study included their ability, or "functional assessment" of maths skills and their socioeconomic background.

condition	form of activity	interactivity	immersion	views
Interactive VR (IVR)	active	yes	yes	multiple
Passive VR (PVR)	passive	no	yes	multiple
Non-VR (LEGO)	active	no	no	single (top-down)

Table 6.1: Activity, interactivity, and immersion for each of the main study conditions

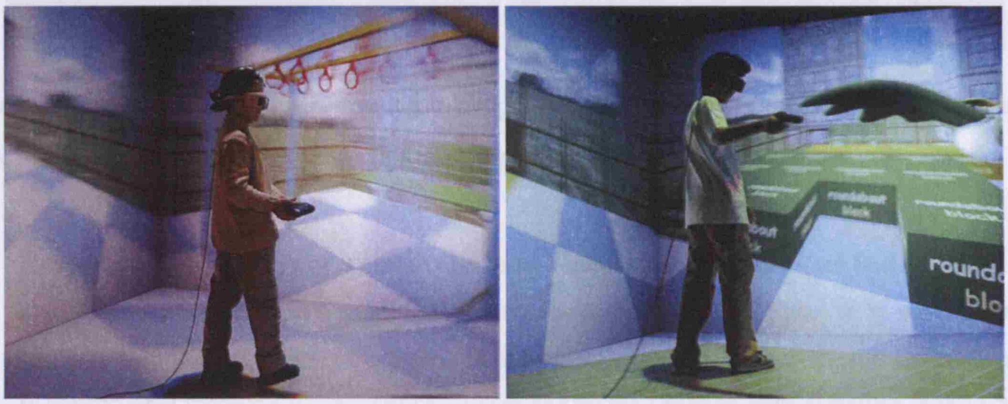

Figure 6.1: Images of children participating in the interactive VR condition of the main study.

In the end, however, due to practical reasons related to recruitment, participants were not preassigned to the conditions of the study according to aptitude, gender, age, or socioeconomic background, even though every effort was made to keep an even spread across conditions where possible.

6.1.1 Experimental conditions

The experiment was designed to include three conditions: two experimental VR conditions and a non-VR condition against which comparisons were made. The two VR conditions involved activity within the virtual environment of the CAVE, in which case the participant was immersed in the 3D re-construction of the playground (the "Virtual Playground" described in Chapter 5). The third condition involved a non-VR activity using LEGO bricks. Specifically, the three conditions of the main study were:

- *Interactive VR (IVR) condition*. The participant of the IVR condition was asked to actively design the playground in the 3D space, having full control over the interactive features of the system and the use of the interaction device. The task was similar to playing with a virtual construction kit or a computer game. Before starting, the task was explained to the participant who had a chance to practice moving blocks around in the virtual space of a training environment (see Appendix B.1). Following training, the participant actively explored the virtual surroundings and was reminded by the observer to explain her actions in the environment. All forms of system feedback described in Section 5.2.3 were available to the participant.
- *Passive VR (PVR) condition*. This took place in the same immersive environment as the IVR condition; only, in this case, a pre-recorded sequence of actions involving the re-design of the

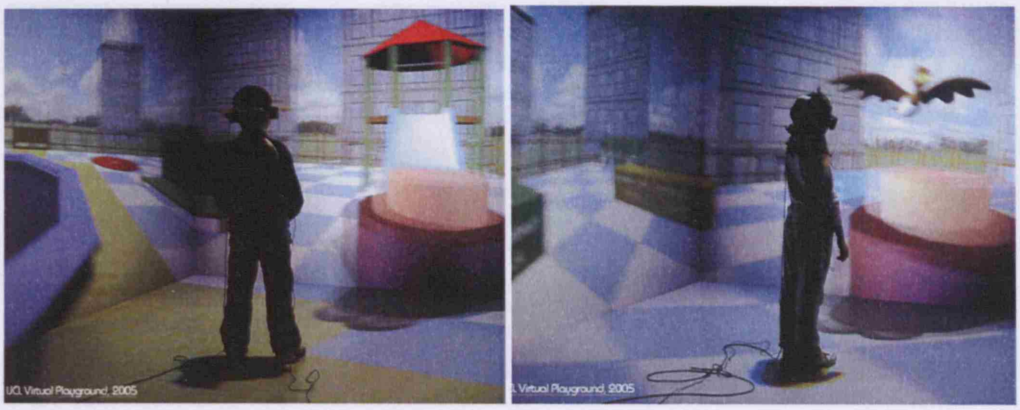

Figure 6.2: Images of children participating in the passive VR condition of the main study. The virtual robot was programmed to be positioned a few centimetres ahead of the user.

playground was played out by a virtual character, a robot named "Spike"[1] (see Section 5.2.4). The participant stood in the space wearing the stereoglasses and observed Spike as he went about listening to the rules and moving the blocks as in a video sequence. The participant was encouraged to predict what Spike's actions would be, prompted by the observer with questions such as "what would you do now if you were Spike?". After the robot completed each task successfully, the participant was asked to explain why Spike had done what he had done and if it was understood.

In other words, in the case of the passive VR condition, the participant in the study was immersed in the VE but did not have the ability to interact with it. Interaction took place between the system and the virtual robot, which the participant could observe. Consequently, the interaction experience for the participant was not a first-person experience in the kinaesthetic sense; the participant could not act upon or control the environment but was able to experience all system feedback that the robot received.

This condition could be considered as the crucial 'control' condition in terms of the research question posed by this thesis, since the participants in this case are not directly ("first-hand") subjected to the full interactive features provided by the VE.

- *Non-VR (LEGO) condition.* The participant who took part in the non-VR condition did not experience virtual reality at all (in fact, did not even know that a virtual playground existed). Instead, an activity was carried out using a physical model of the playground made with LEGO parts (Section 5.3 and Figure 6.4).

The activity involved the redesign of the areas of the LEGO playground on a grid-like floor plan, similar to seeing the playground from above in the virtual reality environment. As in the Virtual Playground, the differently coloured bricks represented the swings, slides, etc., which the participant had to position according to the rules provided on cards (Figure B.11). However, although each participant was actively involved in designing the playground, no response or feedback from

[1] The name "Spike" was given to the robot by one of the participants, after commenting that the robot's arms are like "spikes".

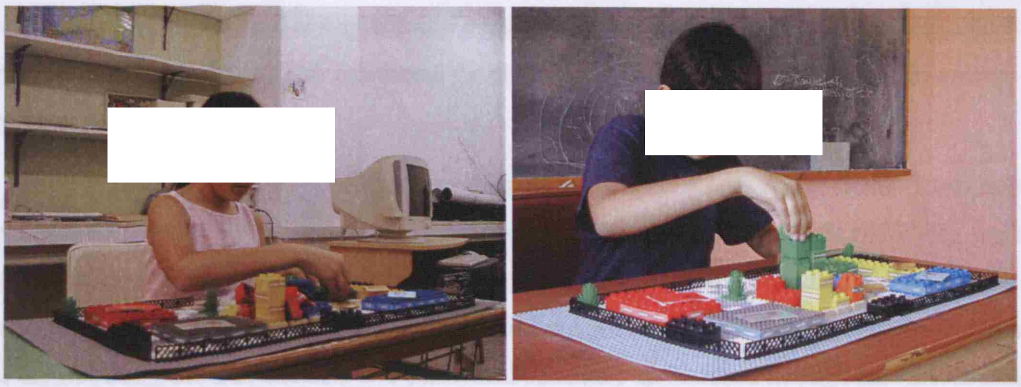

Figure 6.3: Images of children participating in the non-VR condition of the main study.

the system existed -the LEGO playground obviously had no such feedback mechanism built in to it (see Table 6.1).

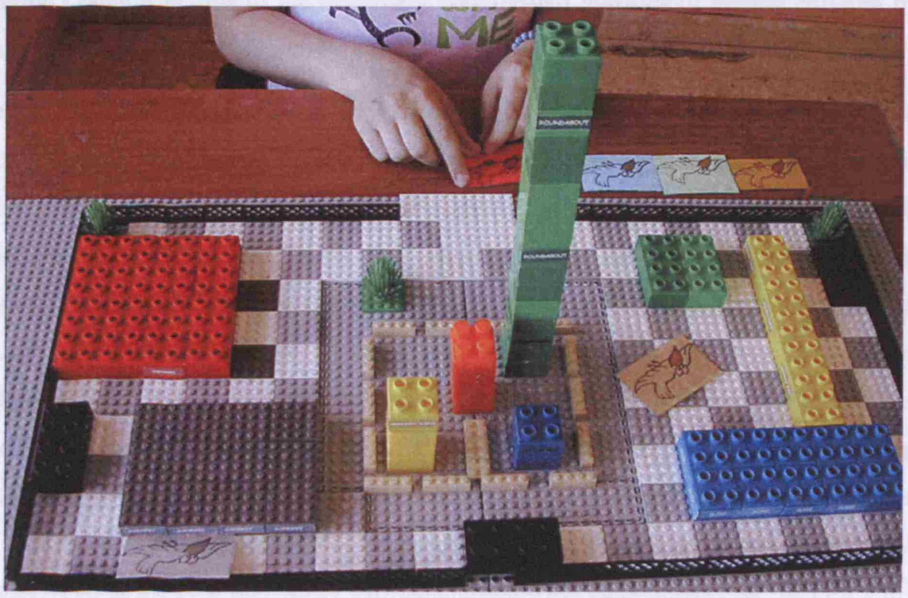

Figure 6.4: A LEGO playground was used with participants that formed the non-VR group. Here is a view of the LEGO playground during user activity. The coloured cards were used to display, in written form, the rules for each area (see also Figure B.11).

6.1.2 Participants

The first issue that needed to be handled with regards to the main study was the recruitment of participants. The initial goal was to have as many as possible, with an equal number of boys and girls and an equal distribution according to aptitude (see Table 6.2). The age of the participants sought for the study was between 8 and 12, that is typically 4th, 5th and 6th year in school. The decision for the specific age group was guided by Piaget's theory of cognitive development (Piaget, 1973), according to which children in elementary and early adolescence are in the concrete operational stage. In this stage, intelligence is demonstrated through logical and systematic manipulation of elements related to concrete objects and operational thinking develops. This reinforces the choice of individuals in this age group in order to best study the development of learning.

Finally, a total of 50 (N=50) participants took part in the main study. Approximately two thirds of the participants used the VR system in the two different experimental groups (IVR and PVR), while the other third of the participants formed the non-VR group and performed the tasks using LEGO. The participants were recruited from various sources including the All Souls Primary School in the Westminster LEA, the Hellenic School of London, and individual educators approached through the various research projects at the Institute of Education, the Museum Group, the BBC's Factual and Learning department, and the NESTA Future Lab's Planet Science newsletter (see Appendix C.8). Additionally, a number of individual parents with children in the appropriate age group were contacted through friends and collaborators, as this was found to be a more focused and flexible solution for attracting individual students and avoiding issues in accommodating larger groups. The final number of participants was different for each condition (Table 6.3), due to the extremely complicated logistics of getting children into central London and into the university laboratory.

Once recruited, aptitude data was derived from each participant's pre-test scores (but also by collecting information about each student's performance from the teacher or parents). Based on these, students were ranked into levels. Specifically, they were assigned to one of three levels (high level for the advanced students, mid level, and low level). The rationale behind the even distribution of participants of different levels across conditions was to avoid assigning students of high aptitude into the same group, as well as to avoid a ceiling effect, where advanced participants would find the exercises to be too easy. At the same time, aptitude treatment could facilitate the analysis of questions such as if the VR experience helped good students more, less, or made no difference, or, if boys who performed better than girls in the pre-test, also did better when using the VE and vice versa, etc. However, the problem encountered with recruiting children meant that preassigning participants into the three conditions based on their aptitude was not possible since the final number of participants could not be predicted; for the IVR and PVR conditions, assignments were random, while the participants in the non-VR condition were children from two different classrooms. Socioeconomic background of participants was also thought to be a potential factor as it usually affects the type of school that participants go to (urban school, rural school, public school, etc.) and could relate to aptitude. However, as the children that finally participated in the study were mostly from central London schools, this factor was not examined further.

Since balancing according to aptitude and socioeconomic background was not possible, an even spread according to gender was attempted although, again, the practical difficulties encountered in recruiting the participants and the fact that they were recruited from diverse sources, prevented an equal number of boys and girls being allocated to each condition as planned (although an equal number of boys and girls was achieved overall). Age became the main criterion for recruiting participants, although it could not be the determining factor for finding children that had been taught fractions in school. It was soon apparent that the understanding of fractions varied greatly between participants of the same age. In

condition	boys	girls	total
Interactive VR (IVR)	8	8	16
Passive VR (PVR)	8	8	16
Non-VR (LEGO)	8	8	16
	24	24	

Table 6.2: Planned number of participants to be assigned to conditions.

condition	boys	girls	total
Interactive VR (IVR)	8	9	17
Passive VR (PVR)	9	5	14
Non-VR (LEGO)	8	11	19
	25	25	

Table 6.3: Final number of participants randomly assigned to the three conditions of the main study.

addition, as the British school system varies in the way school years are defined, the ability that students had to solve fraction problems ranged between the different ages, the different schools, and possibly the different teaching approaches. For these reasons, in addition to their age, the other question asked when recruiting participants was if they had been taught fractions in school. In the end, each student's ability, as judged from the results of the pre-test and the information collected from the parent or teacher, became the defining factor of the student's level of knowledge when coming into the study.

6.1.3 Experimental methods

As discussed in Section 3.1.1, the instruments that were used to evaluate children's activity included direct observation, a conversational semi-structured interview, and written assessments of the topic (written questionnaires prior to and after the experimental tasks).

An effort was made to keep the duration of the pre-test, the actual task, and the post-test under 30 minutes each. However, this varied depending on the child. For participants in the VR conditions, short breaks were encouraged throughout the experience (at 10 to 15 minute intervals) to prevent any possible effects of simulator sickness and discomfort. The informal interview was held with each participant after the experience for a duration of 10 to 15 minutes. Overall, the duration of the experiment for each participant, including training, pre-test, main task, post-test, and interview did not exceed 2 hours (see Table 6.4), while the non-VR condition was usually significantly shorter.

6.1.3.1 Consent

As mentioned in Section 3.1, the study was approved by the University College London's Committee on the Ethics of non-NHS Human Research. For the main study, the informed consent form was completed

TRAINING (IVR or PVR)	3min
PRETEST	30min
MAIN TASK (IVR, PVR, or LGO experience)	30min
POSTTEST	30min
INTERVIEW	15min
Total:	2 hours (max)

Table 6.4: Duration of experimental procedure

by all participants' parents or guardians. In the case of the VR conditions, parents or guardians brought along the completed consent form or completed it on site. In the case of the non-VR condition, the completed forms had already been collected by the teachers and given to the researcher on the days of the experiment. More information on the process of gaining parental consent can be found in Appendix C.1 and an excerpt of the application forms in Appendix E.

6.1.3.2 Participant demographics and profile

As a first step to the study, a simple questionnaire was given to each participant with the purpose of collecting basic demographic information and determining the level of prior experience with computers, game playing, and virtual reality. Specifically, the questionnaire consisted of nine questions. The factual questions asked the participants to enter their names, gender, age, school, and year in school. The 'prior experience' questions inquired about the amount of computer use at home, the amount of game play, the participant's favourite game and an open ended question about virtual reality (what it is and if/where it was experienced before), which the participants had to respond to in their own words. The questions regarding computer use and computer game play provided four possible responses, ranging from 'no/never' to 'yes/every day', which were presented in a Likert-style form.

A sample of the user profiling questionnaire can be found in Appendix C.2.

6.1.3.3 Pre-test

A questionnaire with maths questions that were based on the fractions questions found in standardised tests (such as the Key Stage 2 SAT mathematics and science test) was constructed with the help of two of the collaborating teachers. The questionnaire sought to reveal students' current understanding of fractions, and included a total of 11 questions (9 plus 2 questions with 2 parts) which covered different kinds of maths problems. The questions involved general fractions questions, fraction comparisons, and questions about fractions represented in a variety of ways. The latter set of questions was included in order to test the participants' ability to translate between different representations of fractions.

The questionnaire was completed by all participants after the demographics questionnaire and prior to the main experiment (Figure 6.5). A sample of the pre-test is included in Appendix C.

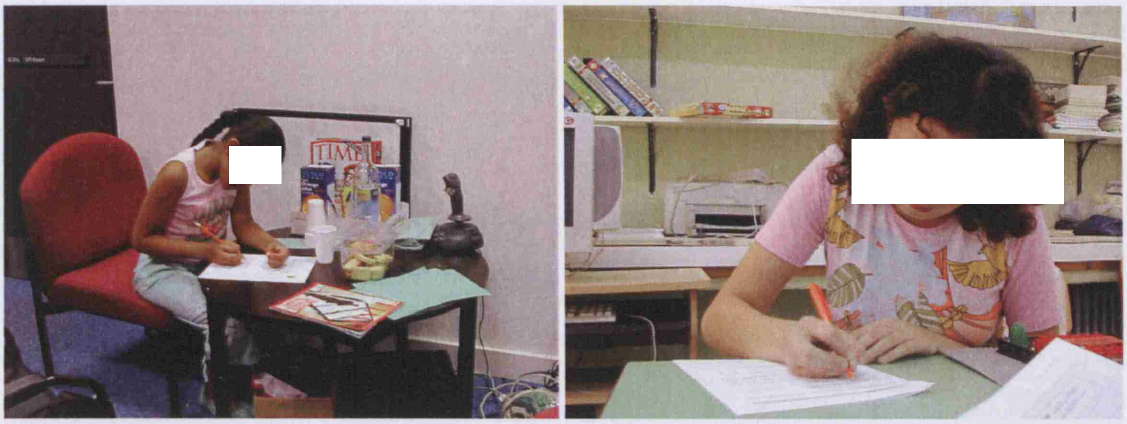

Figure 6.5: Participants completing the pre-test prior to the virtual (left) and the LEGO (right) experiences.

6.1.3.4 Direct observation

The core method used by this research to capture the participant's activity during the main task itself was direct observation, aided by the complete video/audio recording of the sessions and a form of the think-aloud technique. Details about this method were presented in Section 3.1 while the issues concerning the observer's involvement were noted in the discussion of the exploratory study (Section 4.3). Despite the initial aim to be as unobtrusive as possible, a form of 'active intervention' (van Kesteren et al., 2003), where the observer prompted the participants with questions during the experience, was finally adopted as it seemed to work well with the children and not cause breaks in their activity and feeling of presence within the environment. A sample transcript is included in Appendix D.7.

6.1.3.5 Interview

The interviews were of an informal conversational nature, yet a selection of topics was prepared in advance in order to ensure that some kind of structure was maintained. The interviews started out by inquiring about the child's impressions of the VR or the LEGO experience. Questions included whether the participants enjoyed the experience; what they liked or disliked the most; if they thought it was difficult or easy; what they found to be more difficult; what they would do differently if they were to play again; what they would add to the playground to make it better/more engaging; and their perceived utility of the virtual playground for learning maths. Most importantly, the informal interviews focussed on the conceptual problems that were identified by the observer to have occurred during the completion of the task, so students were asked to verbally express their understanding and/or outcome of the problem. The structure of the interview was ultimately defined by each individual's experience and difficulty with the task, and the questions were not posed in a fixed order. This part of the interview was, in many cases, interwoven with the observation process. Overall, the duration of each interview did not exceed 15 minutes (Figure 6.6); in fact, the interviews with children who had answered correctly in the pre-test and did not have problems completing the tasks in the experience were quite short. The interview guide can be found in Appendix C.4.

Figure 6.6: A semi-structured interview followed the main experience.

6.1.3.6 Log files

The Virtual Playground application was programmed to record each user's interaction with the system in the form of a text log file. Log files were collected from all sessions of the interactive VR condition. Each log file recorded the summary of the user's manipulation activity (picking and placing blocks) for each of the playground elements and the system's feedback events. It also recorded time for each of the important interactive events, e.g., elapsed time from the beginning to the end of the activity, duration of manipulation activity for each of the elements, etc. The log file did not record the user's position or navigation path in the environment, as this kind of information was not considered relevant. An example of a log file can be found in Appendix C.6.

6.1.3.7 Post-test

A written post-test was provided in order to assess students' understanding of fractions after they had completed the experiment activity, in other words to identify if there was any change in their understanding. The post-test was identical to the pre-test in terms of the underlying conceptual requirements, which means that the only differences between pre-test and post-test were in the numbers used for the fractions. As with the pre-test, the questions were designed to give the opportunity to students to show their understanding of fractions in a variety of ways, using multiple representations according to Lesh's model (Section 5.1). The participants were also encouraged to write on their sheet, next to each question, if the question reminded them of any of the tasks in their playground construction experience (an example of this can be seen in Appendix D, Figure D.5).

The post-test was completed after the end of the main experiment and before or after the interview (Figure 6.7), depending on how the child felt after the experience -children who were too excited or needed a longer break were asked to complete the test after the interview.

6.1.4 Experimental procedure

As already noted, each session was conducted with one participant at a time and the duration of the session was approximately 2 hours for each child (see Table 6.4), whether the session was held in a

Figure 6.7: Participants completing the post-test following the virtual (left) and the LEGO (right) experiences.

virtual environment or with LEGO. However, the rest of the procedure differed slightly between the experimental VR conditions and the non-VR condition, due to the different apparatus.

In the case of the virtual reality conditions, each participant was accompanied to the study location (the University College London's Department of Computer Science, located in central London) by one or both parents or guardians. The study took place in two different rooms of the laboratory, starting from the entrance area then moving to the VR room and then returning to the entrance area for debriefing. The entrance area was equipped with chairs and a table where the forms, questionnaires, crayons, water, juice and cookies, and magazines for the parents to read while waiting were kept. An introduction to the study and practical information about the procedure were given to both the child and the parents by the researcher. The parents were asked to complete and sign the necessary consent forms (see Appendix E for the full approved UCL Ethics board application and forms), while the participant was given the user profiling questionnaire. The participant was then asked to fill out the questionnaire with fractions questions, as described previously. The exact same questionnaire was given in all three treatments.

Once all questionnaires were completed, the participant took part in one of two VR conditions, either the interactive or the passive VR condition, as described in Section 6.1.2. Each child participated in only one of the conditions of the study (between-groups design). The participant and the observer moved to the VR room in order to take part in the main experimental activity in the CAVE (described in Section 3.1.3). The parent was free to watch the session if the child approved (the positions of the participant, the observer, and the parent(s) in the VR room are shown in Figure 3.3). The researcher explained the technology and fitted the glasses, head tracking cap, and microphone onto the participant. The interaction device was also given and explained to the participant. All participants, whether in the interactive VR or passive VR condition, took part in the VR training session (see Appendix B.1). The participants who were going to take part in the passive VR condition were told that although they were trained to use the interaction device, in fact they would not actually use it in the main study, but that a robot would be "using" it instead. When the training was completed, the researcher asked the participants if they had any questions and then proceeded with the main program.

For the IVR condition, the nature of the study was such that the student was free to act or interact for as long as she wished with the playground, using the wand to navigate around the virtual world, and to select and manipulate virtual objects within that world. For the PVR condition, the participant watched a predetermined sequence of actions played out by a robot (Section 5.2.4). This "immersive video" had a duration of 27 minutes. In both cases, the observer was constantly present, encouraging the participant to explain her/his actions while doing (by thinking aloud). The observer also made sure to ask the participant every 10-15 minutes if he or she wanted to take a break.

In the case of the non-VR condition, the researcher visited two collaborating schools on a number of different days and carried out the sessions with each one of the 19 participants who had agreed to participate in the schools' computer room during specially arranged after-school hours. In this case, the parents were informed by the teachers, who had sent the information pack home with each participant one month prior to the study, and had arranged for each child to stay after class. In contrast to the VR conditions, no parent was present in any of the sessions of this condition; the completed parent consent form was brought from home by the participant. The consent form was a simpler version of the one shown in Appendix C.1, since it excluded the questions concerning the virtual reality apparatus. The same user profiling questionnaire and pre-test as in the experimental conditions were given to the participants. Once completed, the activity with the LEGO playground could begin (Figure 6.4). The activity involved the design of a playground on a grid-like floor plan, similar to the top-down view of the virtual reality environment.

In all cases, after the main experience was completed (activity in the interactive VR scenario, participation in the passive VR scenario, or activity with LEGO bricks), an interview was carried out. Every participant was interviewed about her experience by the observer, who noted the specific actions which the participant had problems with, and directed the participant to reflect on these accordingly. Finally, the participant was asked to complete the post-test, which included questions related to fractions, similar to the pre-test.

6.1.5 Pilot study

A pilot study was held as part of the design process of the experiment for both the non-VR (LEGO) condition (with 3 children) and the interactive VR (IVR) condition (with 4 children). No pilot study with children was carried out for testing the passive VR system, i.e. for the version of the Virtual Playground in which children did not have the ability to interact but instead watched an avatar doing so. However, during the programming phase of the avatar and after the code had been completed, the PVR version of the VP was tested out with ten adult volunteers. None of the data from the pilot study were used for the analysis of the main study.

The goal of the pilot study was twofold: on the one hand to try out the various aspects of the playground models (both virtual and physical) with children and improve their usability; on the other hand to go through all steps of the experimental procedure and identify related issues so as to resolve them before the main experimental study. Thus, an attempt was made to replicate as much as possible the main study environment and procedure. However, in practice, the procedure planned for the main study was not followed fully for the pilot study. That is, the pre-test and post-test questionnaires were given to the children to complete, but only optionally. Also, the observer assumed a very active role during the pilot study experiences and helped the children on both a usability and a conceptual level by asking questions and prompting them to try things out, intervening more than would be required for the main study. Figure D.13 in Appendix D includes images of the children that participated in the pilot study.

6.1.5.1 Pilot study for the LEGO playground

A pilot study with three children, all girls between 8 and 9 years of age, was held for the condition that involved the LEGO activity. The study was very useful in clarifying the procedure to be followed for the main study. All three children in this pilot had difficulty in understanding what to do and, most importantly, sought confirmation or an indication of when they were done, expecting the researcher to tell them if they had completed each task successfully. The lack of any kind of feedback, whether from the play model or from the human researcher, was very unusual and frustrating to them. In this case, the pilots helped to structure the observer's role and "storyline" in that the observer could define and practice the type and amount of intervention that would be made during the main study.

6.1.5.2 Pilot study for the Virtual Playground and observations

In piloting the VP, an earlier phase of usability testing had been carried out with adults, in order to sort out technical and operational issues, such as the duration of the training environment, the volume and duration of the sounds and so on. This phase turned out to be more useful than expected, as adults, it seemed, had greater difficulties and less patience than children when using the technology, therefore being harsher critics.

Four children, one girl and three boys, participated in the pilot experiment of the Virtual Playground, held in October and early November of 2004. The study took place on different days for each participant and each participant was accompanied by one or both parents who had first completed and signed the necessary consent forms, as would later be the case in the main study. In all cases, except for one, the virtual experience lasted for about 30 minutes, in which time the participants completed all the tasks. The fourth participant did not complete the study due to fatigue, which was caused by an earlier illness (unrelated to the VR experience). The participants' ages ranged from 7.5 years old (PLT01 = the youngest boy) to 12 (PLT04 = the oldest boy). PLT03 (9.5 year old girl) and PLT04 were the only participants within our targeted age group that had been taught fractions in school[2].

As with the exploratory experiment that was described in Chapter 4, the pilot study of the Virtual Playground with children was expected to reveal issues on an operational level and familiarise the researcher with the overall process of the evaluation, so as to prepare the main study. Indeed, the pilot studies were very useful in revealing faults in the design and problems that had occurred in the implementation of the environment. As a result of the pilot studies, a number of improvements were made to the program in order to make the environment more usable. Furthermore, the pilots provided the researcher with some interesting observations on a conceptual level, which are grouped thematically and

[2] The transcription notation PLT01, PLT02, PLT03, and PLT04 is used for each of the participants in the pilot study and O. for the observer.

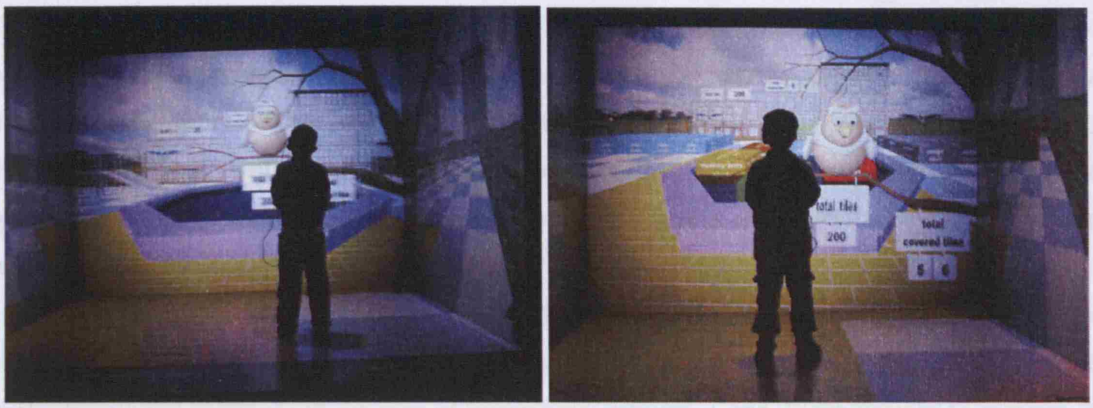

Figure 6.8: Two boys, 7.5 and 8 y.old, interact with the Virtual Playground during the pilot studies.

described below. The process of grouping these observations into themes acted as a rehearsal for the inductive analysis of the data that was performed for the main study and presented in Chapter 7).

The problem of comparing fractions

The chief finding from these pilot sessions in interactive VR, apart from the practical and technical issues with the interface, was the confirmation of the difficulty that children have when asked to compare fractions, mentioned in Section 5.1. This was a consistent finding across all three participants that completed the study.

PLT01, the youngest participant, was able to solve almost all of the simpler exercises with relatively little help from the observer. When he got to the last exercise, which involved increasing the area of the swings (currently a 3 x 4 area of twelve blocks) by comparing two fractions (the fractions $\frac{1}{3}$ and $\frac{1}{4}$) and choosing the number that represents the larger amount, he immediately replied that he would increase the area by $\frac{1}{3}$. However, when asked by the observer how he came up with that result, in other words, how many blocks he believed that $\frac{1}{3}$ represented, he replied that $\frac{1}{4}$ is four blocks and $\frac{1}{3}$ is five blocks. This explained why he chose $\frac{1}{3}$. The observer let him continue with his decision to add five more blocks to the swings area. When he completed the placement of the blocks (inevitably creating a non-rectangular area), he clicked on the red button to switch to "playground mode" and see if his decision was correct. When he saw that it was not, he understood that the area "did not have the right shape", but required help from the observer in order to correct it.

PLT02, an 8 year old boy, was very good in solving the individual fractions exercises. When PLT02 got to the swings, as with PLT01, he immediately responded that one third would make the swings area bigger. However, when the observer asked him how he came up with that response so quickly, he had difficulty in explaining his thought process. He eventually was able to explain that one third of twelve is four, but it did not seem that he had consciously made his decision after performing the calculation; rather his decision was intuitive and seemed to be triggered by the shape of the swings area and what would look correct.

It was later revealed, when talking with the parents, that both PLT01 and PLT02 had not been taught how to add, multiply or compare fractions in school yet, so their responses were, in some cases, random.

This reinforces the observation that some decisions were made intuitively, supported also by the cues provided by the environment (the shape of each area and the surrounding space). It is possible that this intuitive action is closely linked to the form of the representation of the problem and, consequently, the value of VR over formal, abstract instruction as a way of supporting learning. As a result of this observation, a goal for the main study was set, to capture and isolate activity that seems to be a result of intuition, and carefully juxtapose it to the results of the pre- and post-tests.

Similarly, PLT03, the female participant who had been taught fractions in school, made some decisions based on what "looked right". These decisions were evident in two cases, in which she made mistakes with her fractions. In the case of comparison between $\frac{1}{3}$ and $\frac{1}{4}$, she decided to increase the swings' area by $\frac{1}{4}$. When asked why, she replied: "because I counted them and they are twelve, so divided by three they will not be enough... so... [I decided that it will be] four".

O.: So you decided to increase by one fourth...

PLT03: Yeah.

O.: And how many blocks is that?

PLT03: Uh... [*distracted by what she was doing*]. Um, four.

PLT03 made the common mistake, identified by (Mack, 1990), of choosing one fourth as the fraction that results in the larger number. However, she correctly added four blocks (the result of one third, not one fourth) to the swings area. This correct action seemed, in part at least, to be attributed to her intuition rather than her calculations. As with the previous pilot case, this set a goal for the main study to try and clarify such occurrences through careful examination of the pre- and post-tests, the interviews, and the observation data.

The power of the real world

Another interesting situation occurred with the monkey bars. In their incorrect version the monkey bars occupy an area of six blocks, placed in a long strip. The rule communicated to the participant states that the current area is too long and that it must be decreased by one sixth of the area of the sandpit. PLT03 immediately went to the sandpit (which occupies twelve blocks) and decided that the answer is six.

PLT03: ...it's too long [*the monkey bars*].

O.: They have to be one sixth of the area of the sandpit... How much is that?

PLT03: Six. [*with certainty*]

However, when checking the monkey bars again, she became confused, since the monkey bars were already six blocks long, so if she took out six this would leave no blocks on the ground. She was stuck so the observer tried to help:

O.: How would you make that calculation if you had to make it in school, with fractions?

PLT03: I would divide it... so twelve divided by six is two. So, it's two blocks.

With further help from the observer, she managed to complete the task correctly. When asked later why she was confused even though she obviously knew her fractions, she responded that the correct result (two blocks) did not make sense to her, because "in real life the area for the monkey bars could not have been so short". In this sense, it could be argued that the realistic representation of the learning task provoked "common sense", which stood as an obstacle to conceptual change.

Figure 6.9: A 9 1/2 year-old girl interacting with the Virtual Playground.

The choice of different views

Another interesting observation concerns the choice of views within the virtual environment (ground view or top-down view). Neither of the participants chose to use the top-down view, even when counting the blocks in an area. This could be because they simply forgot about it or because they were not used to using alternative tools that could simplify their task when a task could already be performed in more than one way. Nevertheless, this was another interesting point to follow up in the main study. Including a reminder in the interactive VR program that would prompt the children to use the top-down view was considered but finally not implemented due to time restrictions. Instead, in the main study, the observer prompted the participants to use all the buttons on the wand when necessary.

6.1.5.3 Summary of pilot study

In summary, the pilot sessions that were carried out for both the IVR and the LEGO environments confirmed that the children could use the apparatus successfully. In spite of this, some technical (usability) issues were identified and fixed in the VE, resulting in a highly usable system (as shown by the ease with which children in the main study were able to use it). One of the goals of the pilot study, which was achieved, was to improve the system's usability to a maximum level where technical glitches were none existent, so that the evaluation can focus on effectiveness on the conceptual level.

In terms of learning, some generalisations emerged from the observation of the children during the pilot study, especially when examining in detail their activity and reaction to individual problems. Although these pilot sessions were not expected to help in demonstrating added learning value or conceptual change in the participants, they did help in identifying some of the individual sections where interesting contradictions could occur and could be worth focusing on in the main study.

6.2 Summary

This chapter described the main study that was designed to examine the research questions of if and how interactivity influences conceptual learning.

Empirical work was carried out with 50 primary school students (ages 8 - 12), in a between-groups experiment. The experiment was conducted with two different environments designed to simulate a playground: a virtual environment titled Virtual Playground, described in Chapter 5, and a physical model constructed with LEGO bricks. In both cases, participants were asked to complete a set of tasks designed to address arithmetical 'fractions' problems. Three conditions, two experimental VR and one non-VR, were designed with varied levels of interaction and form of activity (Section 6.1.1). The first experimental condition was an interactive VR condition where children had full control over the virtual playground. The other experimental VR condition was a passive VR condition where children observed a robot carrying out the tasks. Finally, a non-VR condition was carried out with children who used the physical model to design a playground with LEGO bricks. The sections that followed described the methods for selecting participants (Section 6.1.2), the experimental methods (Section 6.1.3) and the experimental procedure (Section 6.1.4) used in the main study.

The final part of this chapter (Section 6.1.5) described the pilot study through which the environments used for the interactive VR and the non-VR conditions were tested, in preparation for the main experiment. Four children participated in the pilot study of the interactive VR condition and three in the pilot study of the non-VR condition. Additionally, an iterative process, focussed on testing for usability, was followed for the interactive virtual environment with ten adult users. The pilot study was instrumental in correcting problems before the main experiment and in the design and implementation of the VP; as a result, a number of changes were made to the program. The pilot was also useful in providing insights on the conceptual difficulties that children had with the learning tasks, indicating what to focus on during the main study.

Chapter 7

Analysis of Main Study

The key question addressed in this research is whether interactivity in a virtual environment impacts learning. The main study described in Chapter 6 was designed to examine this question. For this purpose, a virtual environment was developed to simulate a playground, in which children had to engage in tasks that required solving arithmetical fractions problems (Chapter 5). A physical model of a playground made with LEGO bricks was also constructed (described in Section 5.3). Children were tested in three different conditions that varied the levels of interactivity and immersion - two different conditions were carried out in the virtual playground and one with the LEGO. As mentioned in Chapter 3, a methodology was chosen which combines the positive elements of both quantitative and qualitative methods by collating data from questionnaires, direct observation, interviews, and computer log files. This chapter presents first the profile of the children that took part in the main experiment (Section 7.1) and then the results of the quantitative (Section 7.2) and qualitative (Section 7.3) analysis of the data collected from the main experiment. Each of these sections concludes with a discussion of the main findings.

7.1 Participant Demographics and Profiles

This section describes the sample and measures used for the quantitative analysis. Data from a total of 50 (N=50) participants was acquired, 17 from the IVR condition, 14 from the PVR condition, and 19 from the LEGO condition (Table 6.3). The following sections describe the gender and age distribution of the participants, their familiarity with computers and computer games, and their exposure to or perception of virtual reality, as derived through the introductory user profiling questionnaire (Appendix C.2).

7.1.1 Gender and Age

Overall, a balanced distribution of gender was achieved, with a total of 25 male and 25 female participants for all conditions. However, the distribution of male and female participants was not equal within each condition, with 8 boys and 9 girls in the IVR condition, 9 boys and 5 girls in the PVR condition, and 8 boys and 11 girls in the LEGO condition (see Table 6.3). This was due to the difficulties encountered in recruiting the sample (as already explained in Section 6.1.2).

In terms of age distribution, the overall received sample included six children aged 8 (12%), ten children aged 9 (20%), eight children aged 10 (16%), ten children aged 11 (20%), and sixteen children

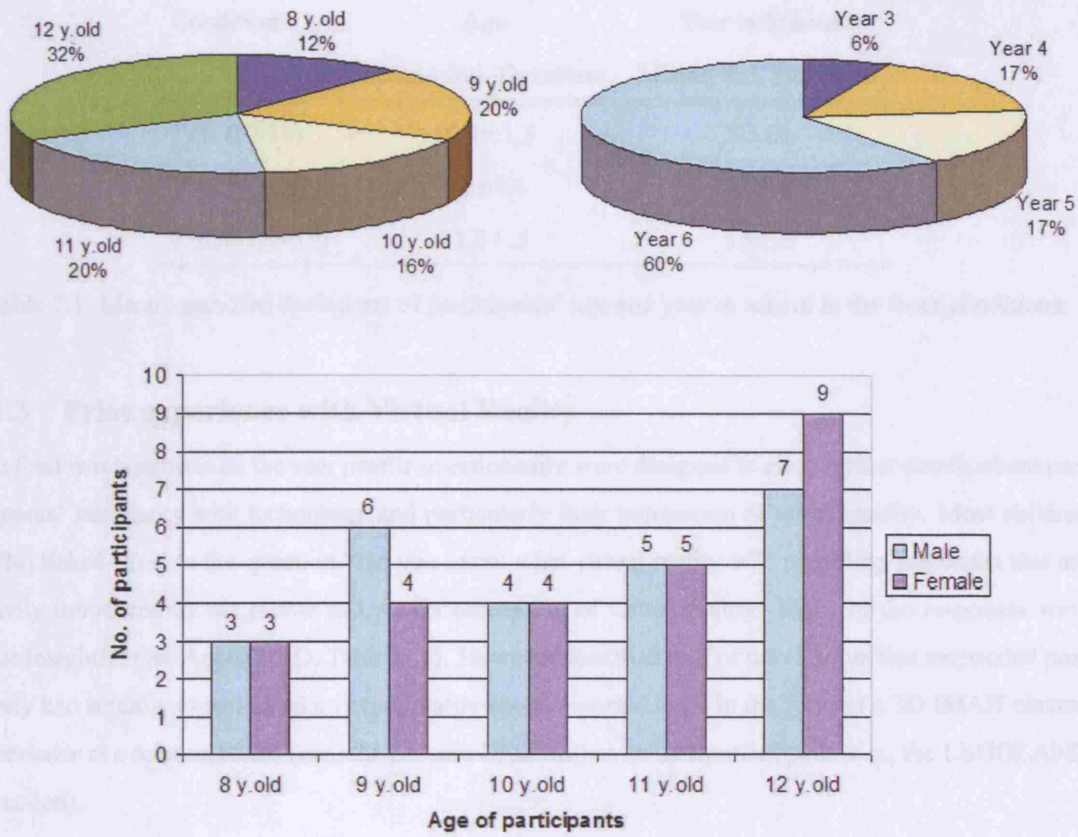

Figure 7.1: Age (top left) and Year in school (top right) distribution of participants and age distribution by gender (bottom).

aged 12 (32%) (Figure 7.1). Overall, the mean age of the participants was 10.4 years. However, the mean age varied significantly with condition (Table 7.1). The LEGO group included only older children (aged 11-12), thus increasing the overall percentage of older children in the study. This was due to the fact that participants in this condition were not recruited individually, as was the case with the VR conditions, but belonged to two collaborating Year 6 classrooms. Consequently, the majority (60%) of the children that participated in the main study were students in Year 6 that had been taught fractions in school and were either preparing for or had already completed their Key Stage 2 SATs (see Section 5.1).

7.1.2 Computer usage and computer/video game play

The majority of the children participating in the main study use a computer frequently (30% as often as every day and 36% every week). Of these children, more girls reported using a computer every day whereas more boys reported using a computer once a week (see Figure 7.2). Computer usage in this case refers to usage for school work, either at school or at home.

A separate question was asked concerning computer/video game playing for which 30% of the children reported playing games daily. As expected, boys reported to be more frequent game players than girls (i.e. reported to play games on a daily basis); however, the difference is smaller than expected (see Figure 7.3). No distinction was made between console (video games) and computer games.

Condition	Age Mean±Std. Deviation	Year in School Mean±Std. Deviation
IVR (N=17)	10.1±1.3	5.3±1
PVR (N=14)	9.1±1.1	4.7±.9
LEGO (N=19)	11.6±.5	5.5±.5

Table 7.1: Mean±standard deviations of participants' age and year in school in the three conditions.

7.1.3 Prior experience with Virtual Reality

The final two questions on the user profile questionnaire were designed to elicit further details about participants' familiarity with technology and particularly their impression of virtual reality. Most children (58%) ticked 'Yes' to the question "Do you know what virtual reality is?" providing responses that are heavily influenced by the public and media perception of virtual reality. Many of the responses were quite insightful (see Appendix D, Table D.1). However, less than half of the children that responded positively had actually experienced a virtual reality show, reported to be in the form of a 3D IMAX cinema experience at a science centre (e.g., the Science Museum) or an amusement park (e.g., the LEGOLAND attraction).

7.1.4 Aptitude distribution of participants

Condition	Aptitude level high	mid	low	Mean±StdDev
IVR (N=17)	4	5	8	6.6±3.1
PVR (N=14)	5	3	6	6.4±3.9
LEGO (N=19)	1	4	14	5.3±2.4

Table 7.2: A frequency table illustrating the aptitude distribution of participants across conditions (in numbers of participants) and the Mean±StdDev of scores on their pre-test (out of $n=11$ questions).

The participants' previous knowledge of fractions was judged by their scores in the pre-test. Additional information was collected through the teachers and/or parents on an informal basis. In some cases, where there was conflict between participants' pre-test scores and their performance in the experiment (e.g., when a participant did not answer some questions in the pre-test but showed, during the experiment, that she had known and fully understood the correct answers beforehand), a note was made for further examination during the qualitative analysis. The number of correct (true=T) and incorrect (false=F) responses were counted for each participant in each condition (IVR, PVR, and LEGO) and the resulting number (from 0 to 11) was used to classify participants' understanding of fractions into low (from 0 to 6 correct responses), medium (from 7 to 9 correct responses) or high (10 or 11 correct re-

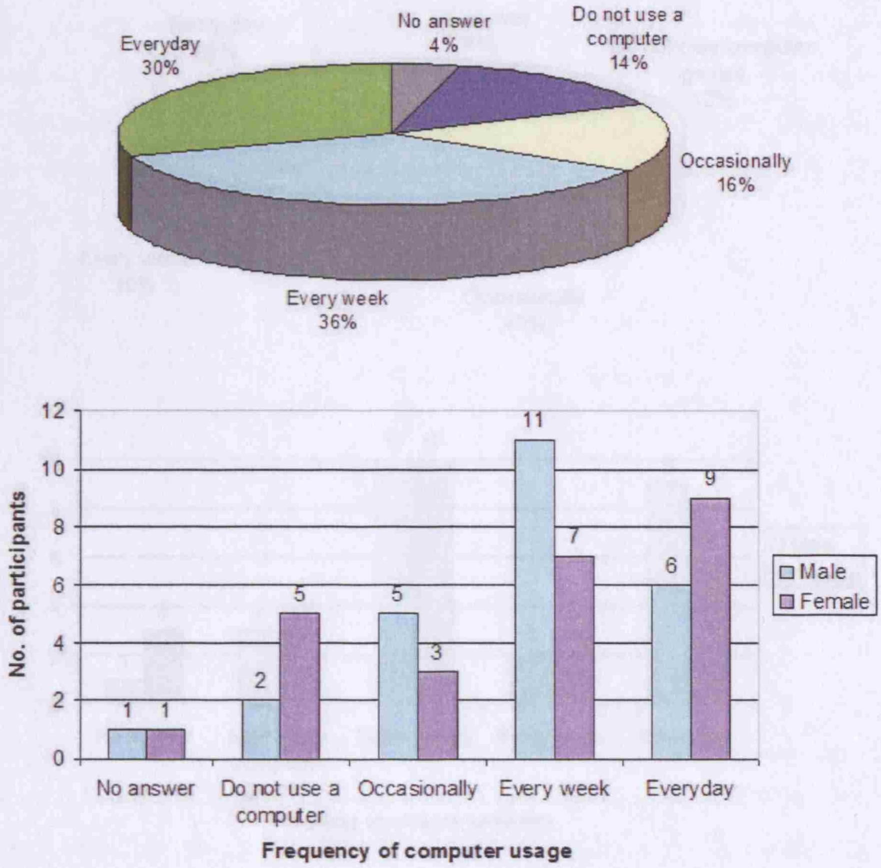

Figure 7.2: Participants' frequency of computer usage and frequency of computer usage by gender.

sponses). Figures D.9, D.10, and D.11 in Appendix D detail the responses from each participant in each condition. Overall, as shown in Table 7.2, the mean pre-test score for the children in the IVR condition was 6.6 (standard deviation of 3.1), in the PVR condition was 6.4 (standard deviation of 3.9), and in the LEGO condition was the lowest, i.e. 5.3 (standard deviation of 2.4).

7.2 Quantitative Analysis

This section describes the application of the statistical method presented in Section 3.2.1 on participant test scores for each condition.

Two response variables were considered in the analysis; *postcorrect*, which corresponds to the number of questions correctly answered after the experiment and *postattempt*, which is the number of questions attempted after the experiment. The independent variable was the condition (IVR, PVR, or LEGO). The explanatory variables included gender ('*gender*'), age of participant ('*age*'), year in school ('*yearinschool*'), frequency of computer usage ('*computer*'), computer game playing ('*gameplay*'), and the number of correct responses on the pre-test ('*precorrect*'). Since the response variables can be treated as binomially distributed random variables, they were analysed using the logistic regression method

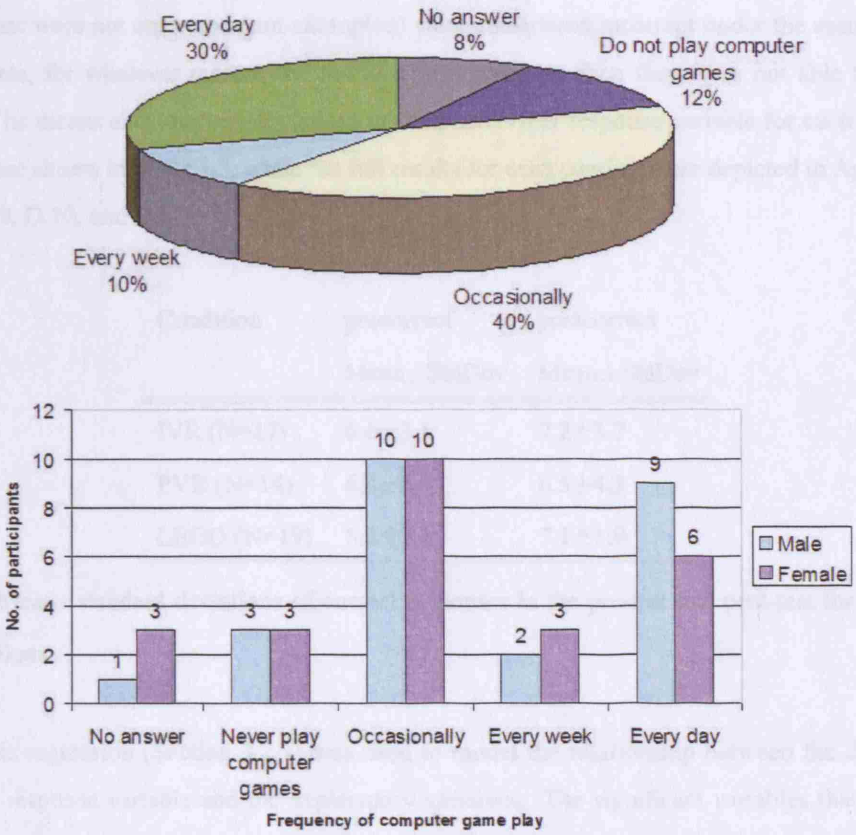

Figure 7.3: Participants' frequency of computer game play and frequency of computer game play by gender.

described in Section 3.2.1.

The variables were constructed from the *n=11* questions of the pre-test and post-test. The number of correct responses were counted out of all responses and the response variables were related to linear combinations of the independent and the explanatory variables. However, the variable *age* had to be statistically eliminated from the regression analyses that were carried out on the response variables, *postcorrect* and *postattempted*, described below in Sections 7.2.1 and 7.2.1 respectively. In other words, the regressions had the linear influence of age already removed.

The reason for this is due to participant ages varying significantly with condition, as shown in Table 7.1. A one-way Analysis of Variance (ANOVA) with *age* as the response variable showed that mean age in the PVR condition was significantly lower than mean age in the IVR condition (t = -2.536) and that mean age in the LEGO condition was significantly higher than the IVR condition (t = 4.707) (df = 47). Therefore this presented a problem in that the effect of condition could not be separated from the effect of age.

Also age is, as would be expected, significantly correlated with *yearinschool* ($R^2 = 0.67$, t = 9.958, d.f. = 48).

7.2.1 Analysis for the 'postcorrect' response variable

As mentioned, *postcorrect* is the number of questions correctly answered after the experiment. All questions that were not answered (not attempted) were considered incorrect under the assumption that if participants, for whatever reason, did not attempt a question then they were not able to answer it correctly. The means and standard deviations of the *postcorrect* response variable for each of the three conditions are shown in Table 7.3, while the full results for each condition are depicted in Appendix D.3 (Figures D.9, D.10, and D.11).

Condition	precorrect Mean±StdDev	postcorrect Mean±StdDev
IVR (N=17)	6.6±3.1	7.2±3.7
PVR (N=14)	6.4±3.9	6.5±4.3
LEGO (N=19)	5.3±2.4	7.1±1.9

Table 7.3: Mean±standard deviations of correct responses in the pre-test and post-test for each of the three conditions.

Logistic regression (Section 3.2.1) was used to model the relationship between the dichotomous *postcorrect* response variable and the explanatory variables. The significant variables that were fitted into the overall model, with the change in deviance (χ^2), the degrees of freedom (d.f.), the direction of the association, and the p-value are depicted in Table 7.4. The table lists only the variables that had a significant impact on *postcorrect*. This means that the variables *gender*, *computer*, and *gameplay* did not have an effect on participants' post-test scores. The chi-squared (χ^2) values in the table indicate the increase in deviance that would result if the corresponding variable were eliminated. Each calculated χ^2 value is compared with the tabulated χ^2 5% value[1], which is 3.84 on 1 d.f. and 5.99 on 2 d.f. If the change in deviance caused by deleting a variable from the fitted model is greater than the tabulated χ^2 5% value then the variable is significant.

Variable	change in deviance (χ^2)	d.f.	association	p-value
precorrect	93.96	1	positive	0
conditionPVR.precorrect	8.02	2		0.0181
conditionLEGO.precorrect			negative	
yearinschool	4.26	1	positive	0.0390
overall	70.61	42		

Table 7.4: Fitted logistic regression for the 'postcorrect' response variable.

[1]These values can be retrieved from a standard chi-squared table or a MATLAB function.

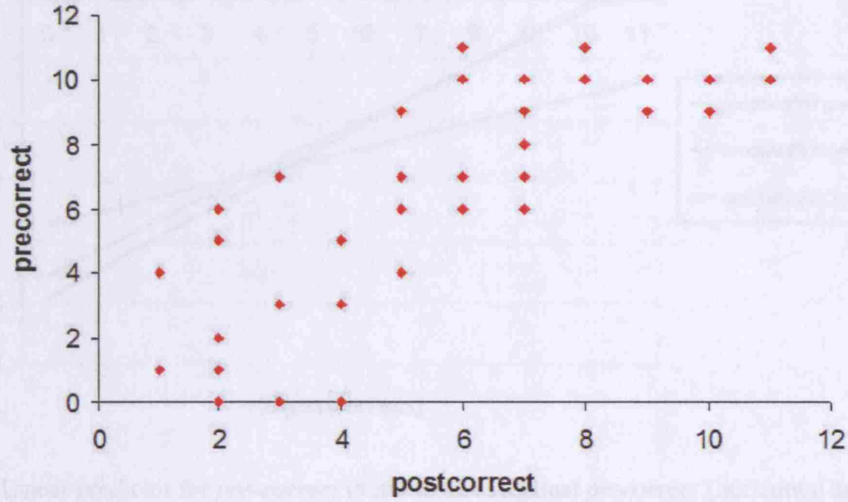

Figure 7.4: Pre- and post-test score scatter diagram depicting the positive association between *precorrect* and *postcorrect*.

Independently, the condition, whether IVR, PVR, or LEGO, did not impact *postcorrect*. On the other hand, independently, *precorrect* was the most significant variable associated with *postcorrect* ($\chi^2 = 93.96 >> 3.84$, d.f.=1), as would be expected (Figure 7.4). However, there was a significant interaction effect between condition and *precorrect* (*conditionPVR.precorrect* $\chi^2 = 8.02 > 5.99$, d.f.=2). Figure 7.5 illustrates the estimated slopes that resulted from the regression equations. This result suggests that there is no difference between the VR conditions (IVR and PVR) on *postcorrect*. However, given the same starting level (*precorrect*), there is greater gain amongst participants in the VR conditions (IVR and PVR) than amongst the LEGO participants. Nevertheless, this is highly tentative because of the problem of *age* being a confounding variable, as described previously. The *yearinschool* also impacts *postcorrect*.

Finally, the overall deviance is 70.611 on 42 d.f. In order for the model to be of a good fit at the 5% level of significance, the overall deviance should be less than 58.125 on 42 d.f. Therefore, although the variables making up the model for the *postcorrect* variable are significant, the fit could be significantly improved by the addition of other variables that were not recorded in this study.

In summary, the model that fit the data for the *postcorrect* response variable showed the following:

- *precorrect* is associated with *postcorrect*, as would be expected. This is a strong positive association and, by far, the most significant result. This variable is important because it removes the effect of the participants' aptitude level when they came into the experiment.
- the slope of the regression for *postcorrect* against *precorrect* is not different between the IVR and the PVR conditions (*conditionPVR.precorrect* is not significantly different from *conditionIVR.precorrect*). The slope of the line is, however, lower for the LEGO condition (*conditionLEGO.precorrect* is significantly different from *conditionIVR.precorrect*). The overall increase in

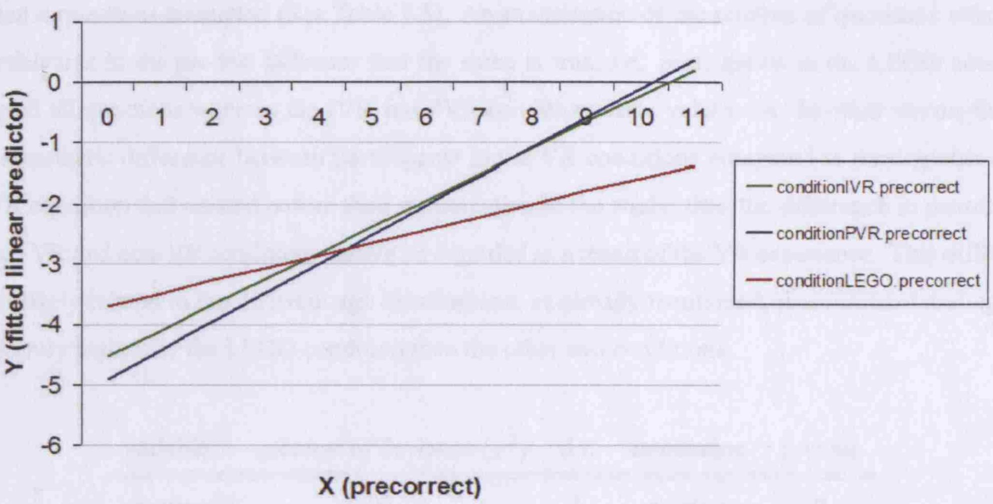

Figure 7.5: Linear predictor for *postcorrect* (vertical axis) against *precorrect* (horizontal axis) under the three experimental conditions.

deviance for removing the interaction term is significant at about 0.02. In other words, the two VR conditions give, on the average, a higher *postcorrect* score for the same *precorrect* score compared to the non-VR condition.

- a strong positive association between *yearinschool* and *postcorrect*, meaning that the number of years in school is significant and positively associated with the number of *postcorrect* responses, as would be expected.

Appendix D.4 contains an excerpt from the logistic regression analysis log file produced by GLIM.

7.2.2 Analysis for the 'postattempt' response variable

The second response variable considered was *postattempt*, i.e. the number of questions *attempted* (whether right or wrong). The same strategy as above was used.

Condition	preattempt	postattempt
	Mean±StdDev	Mean±StdDev
IVR (N=17)	9.4±2.4	8.9±3.7
PVR (N=14)	8.9±2.7	8.5±3.2
LEGO (N=19)	11.0±0	11.0±0

Table 7.5: Mean±standard deviations of the number of attempted questions in the pre-test and post-test for each of the three conditions.

Here, the number of post-test questions attempted by the participants in the LEGO condition is, in all but one case, $n=11$ questions. In contrast, in the VR conditions there were several cases who had less than *n* questions attempted (See Table 7.5). An examination of the number of questions attempted by participants in the pre-test indicates that the same is true, i.e. participants in the LEGO condition attempted all questions whereas the IVR and PVR conditions have values $<n$. In other words, there is some systematic difference between participants in the VR conditions compared to participants in the non-VR condition that existed before their participation in the study; thus the difference in *postattempt* between VR and non-VR conditions cannot be regarded as a result of the VR experience. This difference is most likely related to the different age distributions; as already mentioned, *yearinschool* and *age* are significantly higher for the LEGO condition than the other two conditions.

Variable	change of deviance (χ^2)	d.f.	association	p-value
preattempt	98.19	1	positive	0
overall	133.65	29		

Table 7.6: Fitted logistic regression for the *postattempt* response variable.

Hence, the LEGO condition is not included in the regression analysis for *postattempt*. As before, the variable *age* has also been eliminated from the analysis. In this case, the analysis focusses on examining whether there is any difference between the IVR and PVR conditions. Table 7.6 depicts the significant variables that were fitted into the overall model. Under these conditions, only *preattempt* is significant and positively associated with *postattempt* (χ^2 = 98.19>>3.84, d.f.=1). *postattempt* is also positively associated with *yearinschool*, while no other variables are significant.

In summary, the model that fits the data for the *postattempt* response variable resulted in the following (which is valid only for the IVR and PVR conditions since the LEGO condition results in 11/11 scores):

- a strong positive association with *preattempt*
- a positive association with *yearinschool*
- the slope of the relationship between *preattempt* and *postattempt* is lower for the PVR condition than for the IVR condition. However, this is a 'weak' relationship, i.e significant at 10% but not at 5%.

The overall deviance is 133.65 on 29 d.f. Similarly to the analysis for the *postcorrect* response variable, the overall deviance for *postattempt* should be less than 42.56 on 29 d.f. for the model to be a good fit.

7.2.3 Other variables

In the logistic regression analysis, *gender* was one of the variables shown to have no effect on either *postcorrect* or *postattempt*. The reasons for examining the participants' gender in relation to their performance are due to an expectation that boys may perform better than girls. This expectation was based on public perception that boys are better than girls in maths and on studies indicating that boys' early and sustained exposure to and experience with computer/video gaming places them at an advantage with respect to competence in advanced technological environments (Cassell and Jenkins, 1998). However, the quantitative analysis did not confirm this.

Similarly, frequent computer usage and computer game playing could be thought of as providing an advantage to participants that used the virtual environment. However, the frequency of computer usage and gaming, as reported by the participants themselves on the profiling questionnaire, were not found to have an effect on the number of correct responses or on the number of attempted responses given in the post-test.

7.2.3.1 Performance on individual questions

In addition to comparing overall pre- and post-test scores per condition, it was considered important to examine separately the outcome on two specific questions, Question A5 and Question A2 (the questionnaires can be found in Appendix C.3).

Question A5, on both the pre-test and post-test, dealt with comparison of two fractions. There were two parts to the question, A5a which asked to compare fractions of the same numerator (such as $\frac{1}{3}$ and $\frac{1}{4}$) and circle the one that is larger, and A5b which asked to compare fractions of a different numerator and denominator (such as $\frac{2}{3}$ and $\frac{1}{4}$) and circle the one that is smaller. The reason for focusing on this question is the well known difficulty that children have with comparing fractions, as noted in the literature (see section 5.1) and confirmed by the pilot study (Section 6.1.5). Hence, a comparison of pre- and post-tests on question A5 was used to assess the effect of the study on the student's ability to compare fractions (Table 7.7).

Condition	pre-test	post-test	change
IVR (N=17)	10.5	12	increase
PVR (N=14)	7.5	8.5	increase
LEGO (N=19)	10	9.5	decrease

Table 7.7: Number of correct answers on Questions A5a+b by condition.

The result indicates that the study did not have a significant effect on the ability to compare fractions which would be worth mentioning.

On the pre-test, Question A2 asked the participant to find $\frac{1}{6}$ of twelve. In the playground activity, a similar problem was posed for the monkey bars, which had to be reduced by one sixth of the area of the sandpit, i.e. one sixth of twelve. Another similar task in the playground involved the slide, which required that its area be increased by one fifth of ten. During the activity in the VE or with LEGO, a number of participants seemed to have difficulty in answering this question (see Section 7.3.2.2). The tendency was to use the denominator of the fraction as the result (e.g., answering 6 for $\frac{1}{6}$ of 12 or 5 for $\frac{1}{5}$ of ten).

A comparison of pre- and post-tests on question A2 was used to assess the effect of the study on

Condition	pre-test	post-test	change
IVR (N=17)	9	11	increase
PVR (N=14)	9	11	increase
LEGO (N=19)	5	14	increase

Table 7.8: Number of correct answers on Question A2 by condition.

the student's ability to solve this problem successfully (Table 7.8). However, as with Question A5, no significant differences were found that are worth mentioning.

7.2.3.2 Time and system feedback in IVR condition

As mentioned in Section 6.1.3.6, the computer log file recorded, among other things, the time it took for each participant in the IVR condition to complete the activity. This time refers to the time spent working in the virtual playground and did not include the time in training and the time of the introductory narrative given by the owl.

	Mean±StdDev	Std. Error Mean
Male (N=8)	21.6±6.6	2.3
Female (N=9)	33.2±10.6	3.5

Table 7.9: Time taken to complete activity in IVR (in minutes).

Table 7.9 shows the mean times in minutes. No correlation was found between the time taken to complete the playground in IVR (*timeto*) and *age*, nor between *timeto* and performance on the post-test scores. However, there was a significant negative correlation between pre-test performance and time taken, with students who did worse taking longer to complete the tasks in the VR environment.

Similarly, the examination of the IVR condition participants with respect to the amount of feedback they received from the system showed no correlation. In this case, the 'footpath feedback' was excluded because this was a playground rule that helped mostly in putting the blocks in the pool and not for completing the mathematical tasks.

7.2.4 Discussion

The previous sections began by describing the data to be analysed. This included information on participants' gender, age, year in school, computer usage, gaming, and virtual reality experience, and aptitude, as derived from the participants' responses to the questionnaires. Two response variables were examined using logistic regression: the number of correct responses in the post-tests and the number of questions attempted. In the first case, the most significant association was found between the overall correct responses in the pre-test and the overall correct responses in the post-test. Similarly, in the case of attempted questions, a strong positive association was found between the questions attempted in the

Condition	pre-test	post-test	change
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Overall, these measured outcomes showed to be limited. Even though significant associations were found by the quantitative analysis, these were not useful predictors of either performance or -better yet- improvement on post-test scores due to the existence or lack of interactivity. Moreover, they do not reveal details about what the participant has learned and how, and if the various levels of interactivity or types of system feedback given within the interactive VR condition are contributing. In other words, this analysis was able to provide some evidence with respect to the results on the post-test scores and post-test attempts but not to provide a full response to the basic research question, i.e. whether interactivity in a virtual environment has any effect on children's ability to learn fractions.

As a result, two possible reasons can be identified: that either interactivity has no role to play in supporting learning or that quantitative analysis of the research, on its own, is unable to fully identify this role. As noted in Chapter 3, researchers have recognised that by focusing on quantitative techniques some important parts of a situation can be missed, and that often the best results are achieved through the use of mixed method evaluations where quantitative and qualitative analyses can complement each other. Hence, the qualitative analysis described in the next section was conducted to throw further light on the results of the quantitative analysis and to capture the dynamic nature of the process of interaction in a virtual environment and its effect on learning.

7.3 Qualitative Analysis

The main study has resulted in an enormous pool of data from multiple data sources. A major part of this data is comprised of the video and audio recordings of the participants' activity during the actual experiences designed for the main study. In this section, specific examples of participant activity have been selected and are presented using the Activity Theory framework described in Section 3.2.4. The examples have been categorised into themes based on the problems, contradictions or focus shifts that they illustrate.

Based on previous research and the results of the quantitative analysis, certain expectations were developed regarding the outcome of the qualitative analysis. In terms of "quality of experience", i.e. motivation and enjoyment, it was expected that both the virtual reality experiences (interactive and passive) would be more engaging and exciting for children than the non-VR experience with LEGO. For the same reason, the interactive VE was expected to be more engaging than the passive VE. This expectation was based also on the fact that the interactive version of the Virtual Playground had been explicitly designed to incorporate a rich combination of features to motivate and attract children (e.g., a story line, engaging characters, "magic feedback", challenge, the ability to control and make decisions, etc., see Section 5.2.1). Nevertheless, no metrics were designed to evaluate these aspects of experience, apart from the questions asked in the semi-structured interviews (see Appendix C.4).

In terms of learning gains, the expectation was that the VR experiences would be more effective than the non-VR activity with LEGO. This was partially confirmed by the quantitative analysis in Section 7.2.1. Amongst the VR experiences, greater gain was expected for participants in the interactive VE than in the passive VE.

7.3.1 Experiential factors: affect, presence, and movement

This study has chosen to focus on virtual reality and conceptual learning. Thus, affective aspects of the participants' experience with the environments (e.g., motivation, interest, and enjoyment), presence, and body movement, in other words elements other than interactivity that can define the "quality" of the virtual experience, are of interest only as they relate to the research question -the study of interactivity in VEs- and only to the extent that they have an effect on learning as a result.

Motivation has been related to both learning and interactivity in digital environments. Motivation is a rough generic term for the broadest possible class of non-stimulus variables controlling behavior. The most important of these relate to 'drive' (also considered as the stimulus to action) but the term motivation also refers to preferences, values, and appetites. Anderson et al. (1975) define motivation as the "arousal, direction, and continuance of behavior." In other words, motivation is concerned with behavior regulation: what drives action, how action is directed, and what action is under voluntary control (Chan, 1996). Thus, a number of scholars relate motivation to learning on the premise that it concerns whether a student is willing to learn, not whether the student is able to learn (Chan, 1996). Hence, in the last few years, there has been a considerable shift towards providing motivating learning settings and the building of learning environments that nurture motivation.

The entrance of the computer onto the learning scene and its impact on young users has resulted in the research of motivation in relation to digital environments, especially computer and video games (Provenzo, 1991; Malone and Lepper, 1987; Kafai, 1995). The computer is considered to be an important motivator for learning, and this affective quality has lead many to believe that computers are more advantageous to educational activity than other, more traditional, pedagogical methods. Malone and Lepper (1987) describe three primary characteristics of computer games that directly contribute to motivation: providing a challenge (a goal), creating fantasy (an environment or situation not otherwise available), and provoking curiosity (to make the strange familiar), and expand this framework to add confidence and control as aspects of motivation. Related to confidence, Papert (1980) talks about empowerment. The role of the computer, he notes, has less to do with information and more with giving children a greater sense of empowerment.

These characteristics, particularly the increased sense of control, have been associated with interactivity. As noted in Chapter 2, interactivity is one of the main characteristics to attract children to a digital experience. Nevertheless, there is no direct evidence of interactivity aiding learning as a result of its affective properties. Issroff and DelSoldato (1996) make a distinction between motivation to use a tool and motivation to learn a subject. While interactivity may be one of the most important reasons to use virtual reality, there is no evidence that it is equally or more responsible for supporting learning of a subject. However, it is possible that the former kind of motivation -motivation to use a tool- acts as an initial attractor to the latter -to further engagement with the subject matter.

From a motivational perspective, children have high expectations as to what constitutes a good virtual reality experience, based on their use of commercially developed games and on the popular culture portrayal of virtual reality technology. The majority of the children that took place in the experimental conditions of the main study were already aware of what virtual reality is (Section 7.1) and some had already visited a form of 3D attraction (mostly in cinematic installations such as IMAX theatres and simulators). Thus, there was concern that the virtual environments would not be able to maintain the childrens' interest beyond the initial novelty effect. However, contrary to expectations, motivation was extremely high and lasting for all the participants, as evidenced by their responses to the interview questions and their behaviour and verbalisation during their experience in the virtual environments.

Initial concern was also held during the design of the study for the PVR group. The robot's playback sequence was 27-minutes long. Therefore, having each child stand and watch the robot for so long without being active raised concerns about the interest that the children would have in engaging conceptually with the tasks. Surprisingly, none of the children in the PVR condition expressed feeling tired or bored when watching the robot. It is indicative that not even one of the 14 children that took part in the PVR group wanted to take a break when asked to do so by the observer; on the contrary all of them insisted that they wanted to go on and "see what happens" or "finish it". In fact, taking breaks was something that only three children in the IVR condition that reported feeling dizzy took advantage of -all others were anxious to continue with the activity. The following is one of many excerpts illustrating a typical reaction to the environment by an avid computer game player (IVR10-b8):

David: Can I throw it into the sea? [*referring to the block that he was holding*]

O.: Just throw it anywhere in the pool... just move with your joystick inside the pool and then click.

David: Woohoo! [*exclaims when his action results in the block being dropped in the pool*]

David: I'm dizzy..!

O.: Should we take a break then?

David: No, no, I mean I love this! Could you please put this on Playstation2?

Interestingly, motivation was also high with the participants in the non-VR condition. Most participants expressed their interest and excitement with the LEGO activity. Some noted that they hadn't done something like this before (meaning their use of LEGO for mathematics, especially in their school environment). However, they also expressed their slight disappointment when they had finished the activity, because of the fact that they "didn't know if they had the correct answers", implying in this way that the lack of feedback on their performance was taking away from the enjoyment of the experience.

The effectiveness of a VE has been linked to the sense of presence reported by its users. As noted in Section 2.2.2, interaction has been linked to presence while studies examining user control over the environment (Marshall et al., 2003) and body movement (Slater et al., 1998) have shown positive associations

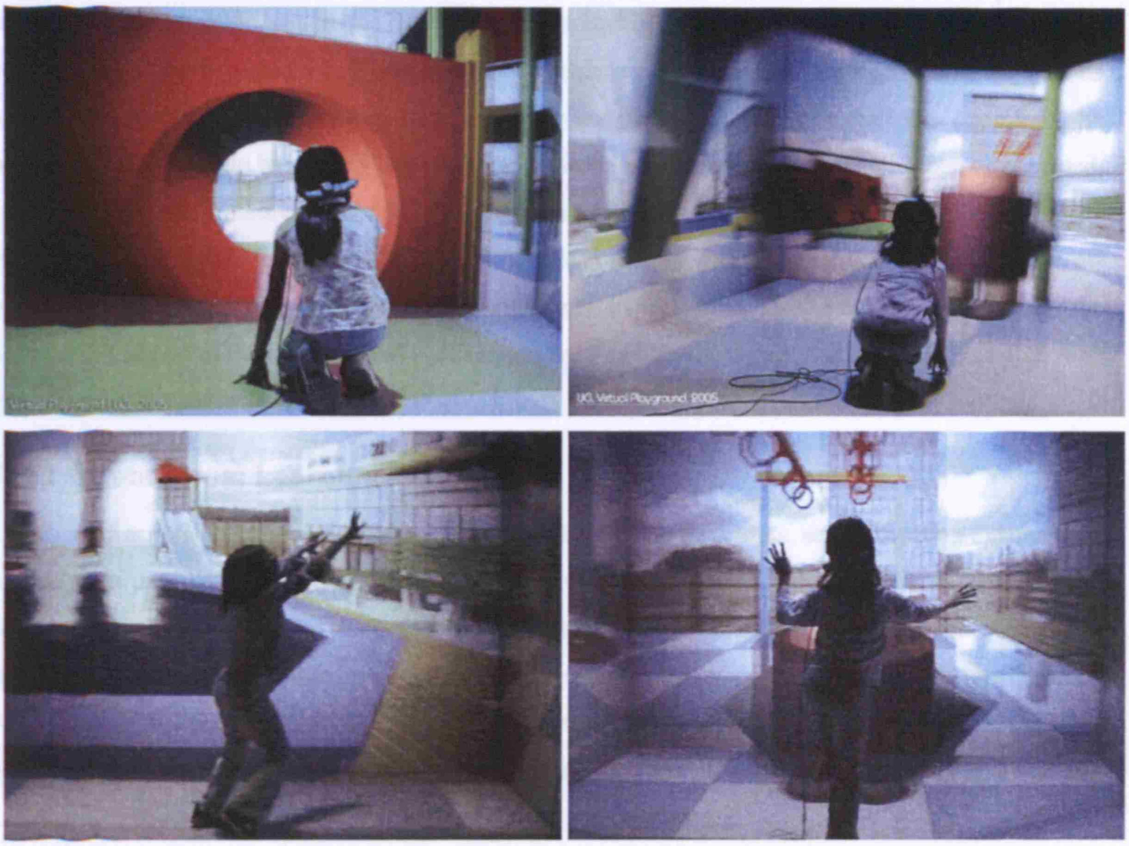


Figure 7.6: Children exploring the completed playground with their whole body, both in the IVR condition, where they use the joystick to navigate (top left) and in the PVR condition where they are guided around the playground by the robot.

with the experience of presence. Researchers have also pointed at the central role of attentional mechanisms, such as 'engagement' and 'involvement', in engendering a sense of presence (Ijsselsteijn and Riva, 2003). Interaction requires becoming involved and engaged with the virtual environment which, in turn, serve as critical factors in engendering a feeling of "first-personness" (Laurel, 1993; Steuer, 1992).

The transcripts from the present study offer plenty of evidence to support participants' involvement into the VE, with statements such as "Hey, watch out, watch where you're going" or "Get out of the way!" directed towards the characters in the environment, "My feet are wet!" when moving over the pool, or "I keep on thinking that I am in a real playground". The amount and nature of body movement is also indicative of the participants' level of involvement indicating enjoyment and a sense of "being" in the environment (Figure 7.6). The quantity of such statements and body movement was not measured and compared in detail between the IVR and PVR environments, as this was considered to be outside of the scope of this study. However, both the IVR and PVR conditions seemed to afford an equal amount of verbalisations and movement, even though the IVR participants were required to move more in order to complete the tasks.

Overall, the methods used to measure motivation, enjoyment, and presence were based on participants' informal responses in the interviews and examination of the transcripts that recorded direct observation of the experiences. These were not adequate measures to derive significant conclusions about the influence of these elements on interactivity and potential learning in the VEs. Therefore, the only conclusion that can be made is that both VR environments were extremely motivating, as expected, confirming also the results of a number of past research studies in VR and education (see Section 2.3.2). However, contrary to expectations, the non-VR (LEGO) activity was also engaging and motivating, albeit at a different level in terms of fulfilling participants' expectations. Due to the lack of feedback, the activity did not achieve "closure" and participants were not aware if they had reached their goal, and consequently not rewarded for it.

7.3.2 Conceptual Learning

Upon examination of the pre- and post-tests and the observation transcripts, some emerging themes were identified in terms of the learning content, related to the tasks that proved to be difficult for many of the participants. The problems that more children seemed to have difficulty with were concentrated on issues such as the ones brought up in the quantitative analysis, namely fractions comparison (Question A5) and the tasks that related to Question A2 of the tests. These problems were identified on the basis of the frequency with which they occurred in all three of the conditions of the study (IVR, PVR, and LEGO).

The basis of the qualitative analysis is the general Activity Theory system described in Section 3.2.4 and Figure 3.5. In AT terminology, each problem or task in the playground activity becomes an *Object* with an immediate, defined goal (the Object to solve $\frac{1}{5}$ of 10 in order to correct the slide area, for example). All Objects are part of the overall learning goal or outcome, which is to understand fractions. Understanding fractions is an implicit outcome for the participant; on the other hand, to design a correct playground is the explicit goal. This analysis is interested in examining if the implicit outcome of understanding fractions takes place and to identify the role of interactivity, as a property of the tool (VR), in achieving this outcome. For the purpose of this analysis, the tasks have been grouped thematically to form categories of fractions problems where interesting contradictions (see Section 3.2.3) were observed or where cues/features of the system prompted participants to act or respond in similar ways. It is the working through contradictions or the focus shifts (deliberate changes of focus of activity) (Bødker, 1996) that are analysed and that, according to AT, are sources of development (Kuuti, 1996). The examples presented in each of the thematic categories below are extracted from the IVR and PVR conditions (Figure 7.7) on the basis of their being representative of the themes they illustrate. These examples were also selected because they correspond to participants that were more able to verbalise the reasons of their actions. Despite the fact that contradictions occurred on the same themes and learning problems in the non-VR condition, the activity with the LEGO bricks did not provide opportunities for resolution, in other words, feedback to the participant if the solution was right or wrong. Thus the participants' objective of designing a correct playground with LEGO was not reached, since all but one participants (the one being the only child who performed well on the pre- and post-tests) did not complete a correct playground in its entirety.

7.3.2.1 The problem of ordering fractions

Ordering fractions was difficult for many of the participants in the study, as expected. Both the extensive reference to this problem in the literature (see Section 5.1) and the observations from the pilot study (Section 6.1.5) had pointed to the fact that students tend to apply whole number strategies when comparing fractions. Furthermore, Behr et al. (1986) have found that this problem is amplified when the ordering task is embedded in a verbal problem-solving situation, as has been the case with the way the tasks were communicated to the participants in this study. Hence, it is not surprising that most examples of conceptual conflict occurred with the swings task, which involved increasing the 3 x 4 area of the swings by comparing two fractions (the fractions $\frac{1}{3}$ and $\frac{1}{4}$) and choosing the number that represents the larger amount. Two examples from the transcripts were chosen to illustrate this theme, one from the IVR condition and one from the PVR condition. Each example illustrates a different kind of breakdown within the activity system.

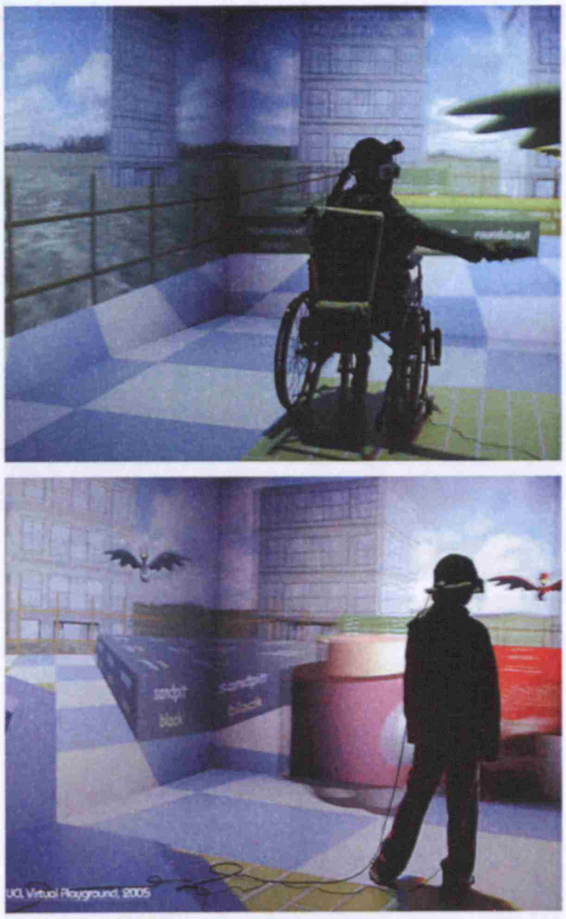


Figure 7.7: A 10 year-old girl (top) interacting with the Virtual Playground and a 9 year-old girl (bottom) observing the robot while he removes blocks from the playground.

__Example 1__

Jenny (IVR13-g10) is a 10 year-old girl participating in the interactive VR condition. Her ultimate goal was, as for all children in the study, to correct the playground. Her immediate goal, or action, in this example was to correct the area of the swings. The tools available for her to perform her action were all the possibilities provided by the interactive VE at the operation level (listed in Table 5.2). When required to choose between a third and a fourth of twelve, she chose one fourth as the fraction that results in the larger number. She picked three blocks from the pool and attempted to fit these three blocks in the correct place so as to complete the task. Jenny tried out various solutions before realising, through an approach of reflection that was guided by her recalling previous experience of system feedback, that she should have chosen one third instead of one fourth:

1. **O.**: Ok, so one third of twelve or one fourth of twelve is gonna give you more?

2. **Jenny**: One fourth

3. **O.**: How many blocks will one fourth give you?

4. **Jenny**: So [*counts the blocks on the ground*] there's twelve blocks... so, three.

5. **O.**: So, where are you going to put these three blocks?

Jenny clicks on her wand's blue button to see the playground from above (demonstrating that she is aware of and able to use the tool in a way that will give her a better, more global, view of the available space for placement).

Figure 7.8: Children using the top-down view to plan the layout of the playground.

In the top-down view (Figure 7.8) she indicates where she plans to place the three blocks:

6. **Jenny**: Two, either on this side... or no, I mean three blocks on around... this bit.

7. **O.**: Towards the fence or towards the sandpit?

8. **Jenny**: Towards the fence.

She returns to ground view and attempts to place the first block on the side of the swing area that is near the fence. This triggers the system feedback message that it is too close to the fence.

9. **Jenny**: Ok, so, on that side... but we can't do it on that side... I think I have to use the whole shape cause that's too close to the sandpit.

10. **Jenny**: Ok, I know what I wanna do. I think. I'm going to bring... [*thinking, but not doing anything*]

11. **Jenny**: Ok, no, it's going to say "too close to the path..." cause if I put these three I think still it's gonna be too close... cause there's four here [*meaning four free tiles*] that might say the shape's not right...

12. **O.**: What do you mean about the shape...

13. **Jenny**: Wait, how much do I have to put, three or four? four! oh! we should do one third, cause one third of twelve gives us four and it'll complete a proper shape.

14. **O.**: How come you didn't think about this from the beginning?

15. **Jenny**: Cause the number four is bigger than three so it just came to my mind straight away.

16. **O.**: You mean one fourth is...?

17. **Jenny**: Just cause the number's bigger it just came to my head straight away.

Meanwhile, Jenny has picked four blocks and has placed them one by one in the correct area.

18. **Jenny**: Ok, red button! [*clicks confidently on the red button*]

Upon clicking on the red button, the model for the swings replaces the blocks that comprise that area, and Jenny completes her task in the playground. Jenny initially focussed on the denominator of the two fractions to give her answer. As already noted, this is a typical strategy, reported in the literature as 'whole-number dominance' (Behr et al., 1986), where students are influenced by their knowledge of whole-number arithmetic (e.g., "$\frac{1}{4}$ is bigger than $\frac{1}{3}$ because 4 is bigger than 3"). In her first attempt to place the three blocks on the side of the swings area where three tiles were available, she received feedback from the system not allowing her to do that. This represents a contradiction between her rules (R_1) and the dominant view of the community, shown as a break between Jenny and R_1 in part (a) of Figure 7.9. This breakdown in her activity within the interactive VE caused her to look around in order to find the appropriate placement for the three blocks. Her prediction of the kind of system feedback that she would get in each case narrowed the possibilities for placement and led her to consider the only appropriate place that was left, and thus revise her answer (lines 9-13).

Jenny could make the calculation (i.e. she knew that a third of twelve gives four) but she was not able to respond to the ordering problem, so part of her rule set was correct but not all of it. System feedback led her to reach her goal by incorporating new rules to her existing set of rules (shown as R_2 in Figure 7.9.b), in other words, by integrating new pieces of knowledge to her existing model. Consequently, her response to Question A5a on her post-test (which was the exact same exercise of comparing one third and one fourth) was now correct (Figure D.5). However, her response to Question

A5b (comparison of two fractions with different numerators) remained incorrect. This indicates that despite her ability to complete the task in the virtual environment by ordering fractions of the same numerator, she was not able to transfer and generalise this rule to a similar problem on the post-test but with fractions with different numerators. She was able to resolve the contradiction but only partially. Therefore it is not certain that the outcome of this process was achieved on a conceptual level, i.e. that deep understanding of concepts of order in fractions was gained.

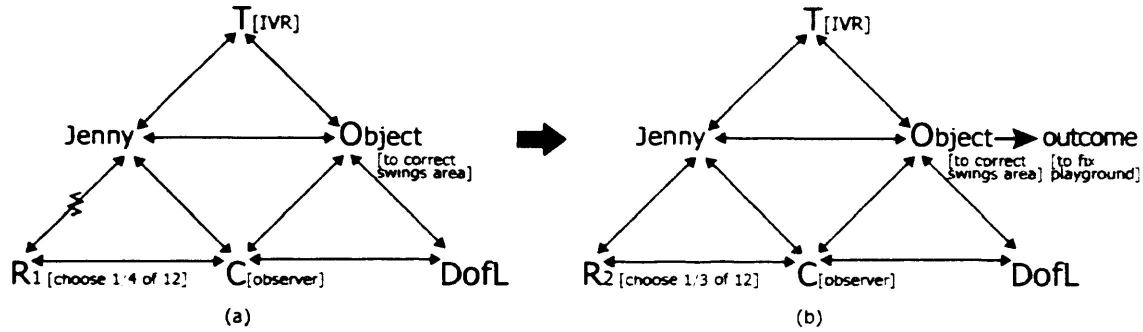


Figure 7.9: An activity system illustrating (a) the contradiction between Jenny's understanding of the rules and the dominant community rule set and (b) how this is resolved by her changing her rules R_1 to a new rule set R_2.

__Example 2__

The effect of system feedback on children's responses was also observed in the passive VR condition, even though in the PVR case the children did not have a chance to respond kinaesthetically to such feedback and to try things out. They did, however, respond verbally, by predicting how many blocks the robot would be placing, thus "guiding" the robot in placing the blocks, and explaining the robot's actions and operations after the task. A similar example to Jenny's response in the case of the swings is Lisa's (PVR10-g9) with the only difference that Jenny could act out her actions. Hence, in Lisa's case, the activity and action remain the same as in Jenny's case but the operations required on behalf of Lisa change. The operations are now performed by the robot, whereas Lisa's operations are restricted to observing the robot and telling the observer what the robot ought to be doing or why he had done what he had done. There is a division of labour here in the sense that the robot is taking on part of the work of fixing the swings area by performing the tasks in VR; Lisa, in her view, is aiding in this process by predicting what ought to be done. Hence, when the red bird finishes explaining the rule for the swings area, Lisa immediately "directs" the robot:

19. **Lisa**: Well, do one fourth because it's the bigger and it says that it has to be the bigger that it can be... so ... [three... four] ...twelve, so uhm, twelve, uhm, four. I think we have to put four over there and that will be it.

20. **O.**: So you chose one fourth of twelve... so four where?

21. **Lisa**: Just here [*showing where the robot has started putting the first block*]

22. **O.**: How come?

23. **Lisa**: Well, cause if we put them there it's too close to the fence [*pointing to the row of empty tiles that is near the fence*], there it's too close to the fence [*pointing to the other row of empty tiles near the other corner of the fence*], now there, there [*pointing to the side near the sandpit*] it's too close to the bench and... here [*pointing next to where she is standing*] it's too close to the path.

Indeed the robot has finished placing all four blocks in the row and the swings are completed successfully.

24. **O.**: Ok, so that was right, the four blocks, but do you remember which fraction the four blocks is?

25. **Lisa**: Uhm, three times [*thinking*], uhhm a third.

26. **O.**: A third... you said one fourth before... so between one third and one fourth, which fraction gives you a bigger number?

27. **Lisa**: One fourth! no. yeah.

Later in the interview, the researcher asked Lisa to try to explain again how many blocks come out of one third of twelve and how many blocks come out of one fourth. She correctly responded that one third of twelve is four and one fourth of twelve is three and then recalled her mistake by realising that "oh yeah so one third is bigger". When asked why she thought that one fourth is bigger she laughed saying that "well, because four is bigger".

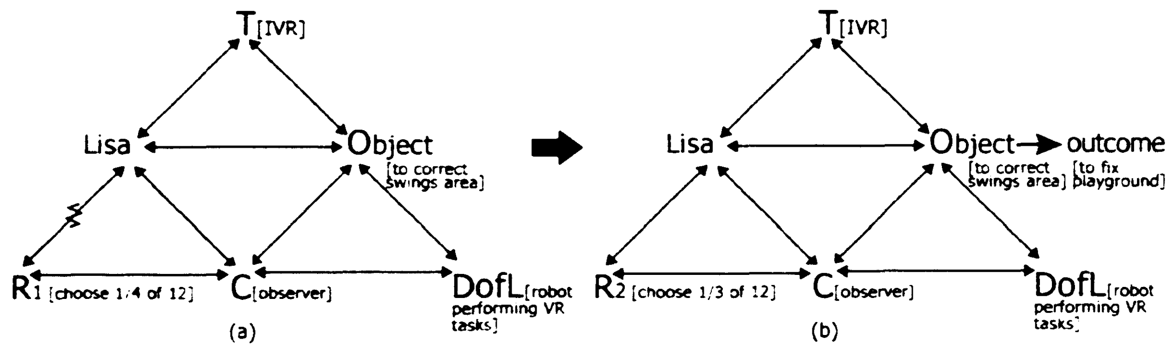


Figure 7.10: An activity system illustrating a contradiction between Lisa's set of rules R_1 and those of the community, which is being resolved as a result of the observer's intervention.

Lisa made the same mistake as Jenny in picking one fourth of twelve as the fraction that gives more blocks and admitted that she had chosen it because of the number four in the denominator being a bigger number than three. However, unlike Jenny, she incorrectly believes that one fourth of twelve is four. Lisa's initial rule set is incorrect as she cannot respond correctly neither to the fractions calculation nor to the ordering of fractions (Figure 7.10). The visualisation of the area and her up to now experience of system feedback helped her to predict what the feedback messages from the system would be and thus decide where the robot would be placing the four blocks, i.e. on the only four tiles that were available (lines 21-23). The robot's actions confirmed her choice and predictions and the playground was completed successfully with Lisa's initial conceptions remaining as they were before she entered the experience (as confirmed by her incorrect response to Question A5a on both the pre- and the post-test). However, when followed up by the observer, Lisa was able to explain the problem correctly and show that she understood why she had been mistaken. Lisa's contradiction with her rules is not resolved during the VR experience but only after she has finished with it, through prompting by the observer. So there is no contradiction between Lisa and the tool (in fact, in the PVR case, there is no interaction between Subject and Tool at all) nor between Lisa and Division of Labour (the robot). This is a case where, similarly to the exploratory case study in Section 4.2.1.2, it is the observer's intervention that caused a revision in the participant's rules. The participant shows that she is not capable of resolving her misconceptions unaided. The observer, in this case, steps out of her role and by questioning Lisa, essentially supports her unintentionally, creating a Zone of Proximal Development. Nevertheless, Lisa's revised understanding, has no long term effect on how she thinks about fractions since, in the post-test, she reverts to her previous misconceptions.

7.3.2.2 Using the denominator as the answer

A common mistake, made by more than half of the participants in the study, was the use of the denominator of a fraction as the resulting number required by the task. This problem was faced with two of the playground elements, the slide and the monkey bars, which involved tasks that required finding one fifth of ten and one sixth of twelve respectively. For example, initially the monkey bars occupy an area of six blocks, placed in a long strip. The rule communicated to the participant states that the current area is too long and that it must be decreased by one sixth of the area of the sandpit (which occupies twelve blocks). The slide area, on the other hand, must be increased by one fifth of ten (see also Figure 5.10). Both the pre-test and the post-test included questions, particularly Questions A2 and A8, that required similar calculations.

Example 1

Annie (IVR10-g10), a 10 year-old girl participating in the IVR condition and attempting to correct the monkey bars area, was unsure of the answer to one sixth of twelve. She believed that the answer was six but wasn't sure about it.

28. **O.:** Ok, so what are you supposed to do?

29. **Annie:** Go to the sandpit and see how much it covers and the monkey bars should only take up one sixth of what the, uhm, the sandpit covers.

30. **Annie:** [*counts*] It covers twelve tiles.

She then goes back to the monkey bars and counts the monkey bars blocks that are on the ground.

31. **O.:** So how many monkey bars blocks are you gonna leave on the ground?

32. **Annie:** Uhm. [*thinking*]

33. **O.:** Do you remember the calculation that you're supposed to make?

34. **Annie:** Uhm, yeah, one sixth of twelve

35. **O.:** How much do you think it is?

36. **Annie:** I thought it was six.

37. **O.:** And how many [*blocks*] are the monkey bars?

38. **Annie:** Six.

39. **O.:** So... if you take six away...

40. **Annie:** ... there'll be nothing

41. **O.:** What do you think the problem is?

42. **Annie:** I'm trying to work it out. I don't know how

43. **Annie:** Uhm. [*picks up one block and drops it in the pool. With five blocks on the ground she clicks the red button but it doesn't work*]

44. **Annie:** No. [*thinking and looking around for almost half a minute*]

45. **O.:** Are you a bit stuck?

46. **Annie:** Yeah. I don't know how to work out one sixth of twelve.

47. **O.:** Is that something you have a problem with in general?

48. **Annie:** Uhm, wait I think... [*thinking*]

49. **Annie:** The bird said that it's too big. [*pausing and thinking*]

50. **Annie:** I'm just gonna try taking blocks away. [*removes one*]

She clicks on the red button but nothing changed. She clicks on the red button again.

51. **O.:** So how many do you have now?

52. **Annie:** Four, it doesn't work [*removes one, leaving three, and clicks on the red button*]

53. **Annie:** That doesn't work. [*removes one, leaving two, then clicks on red button which changes the area into monkey bars*]

54. **Annie:** [*smiles*] Ok.

55. **O.:** So what was the correct answer then?

56. **Annie:** Two.

57. **O.:** Does that make sense to you?

58. **Annie:** Only cause of the two six. Two times six is twelve.

59. **O.:** So how did you come up with six then?

60. **Annie:** Uhm.

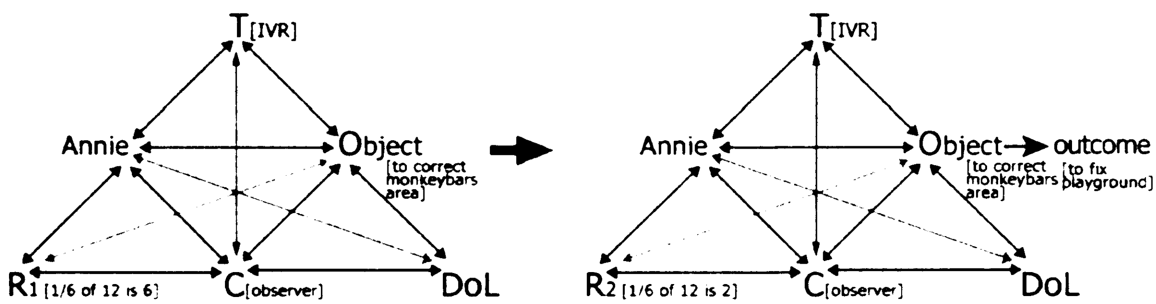


Figure 7.11: An activity system illustrating Annie's understanding of the Rules and then self-reassessment.

Annie has an initial conflict with her own rules R_1 and with what she sees in the virtual environment. Following consecutive trials for which she relied on system feedback, she was able to reach the answer and complete the task and then to actually explain the answer and resolve her contradiction (Figure 7.11). This is an example of the interactive VR system aiding in problem-solving; Annie is able to solve the problem but does not show to have a theoretical understanding of the solution -there is no discourse in her process of trying to solve the problem that shows intentionality of her actions (lines 46-53). Nevertheless, she is able to give a conceptual explanation (line 58), which persisted to the post-test, since the result of Question A2 was now correct. This is evidence of learning through problem-solving that was supported by the interactive VR environment.

Example 2

Like Annie, David (IVR10-b8) participated in the IVR condition giving the same incorrect response to the monkey bars problem. Even though the problem is the same, the examples differ with respect to the resolution of the contradiction. David is a very talkative and animated boy who admits to playing computer games several hours per day, every day. He is very keen on participating in the virtual reality experience and has no problem using the interface even though he has never experienced virtual reality before. He is a very competent player, confirmed by his computer log file which shows that he completed the activity in 23 minutes, even though he didn't know his fractions (as indicated by his low score of 4 correct questions out of 11 on the pretest). The following incident is indicative of his approach to completing the tasks in the virtual playground.

61. **David:** Sandpit is over here... so it'd be, uhm. one two three four ... twelve. What do I have to do again?

62. **O.:** What the yellow bird told you... you have to take away blocks from the monkey bars and leave one sixth of twelve.

63. **David:** Oh easy, I just have to take away half of them. Six and six is twelve.

64. **O.:** One sixth of twelve is how many blocks?

65. **David:** Uhm, six.

66. **David:** One. two. three. four. five. six... [*counting monkey bar blocks that are on the ground*]

67. **O.:** So if you take away six, then there will be no blocks left.

68. **David:** Yeah [*nevertheless, he starts removing blocks from the monkey bar area*]

69. **O.:** So how many are you taking out?

70. **David:** All of them.

71. **O.:** You're taking out all of them?

72. **David:** Yep.

73. **O.:** But then you're not gonna have any monkey bars... you have to have monkey bars in the playground.

74. **David:** I have to take away one sixth.

75. **David:** Oh, I'm supposed to leave four. I've got to leave four, so I'll put that back.

David takes the block he just dropped in the pool and adds it back to the monkey bars area, then presses the red button but nothing happens. He takes it away again leaving three on the ground and presses the red button. He then states that he is going to check again by going to the sandpit and counting.

76. **David:** It says to take away a sixth... I don't get that... it says take away a sixth.

77. **David:** Maybe just leave one behind... oh god...

He then concludes that he probably didn't have the blocks in the right order so he adds blocks and tries once again to leave four behind but in a different configuration. He receives a system feedback message informing him that the fourth block is too close to the bench. He keeps on removing and placing blocks and clicks on the red button every time. He finally leaves two on the ground and the blocks turn into monkey bars.

78. **O.:** Hey you got it right, what did you do?

79. **David:** I just left two of them. Now let's play! Yeeha!

David's is another example of solving the problem by trial and error supported by the interactive VR environment. His incorrect yet firm belief that $\frac{1}{6}$ of twelve is found by subtracting 6 from 12 (line 63) is not altered even when the observer essentially "warns" him that if he leaves no blocks he will not have monkey bars in the playground and thus risks not achieving his goal to complete a correct playground (lines 67-73). He chooses to ignore the dominant rules of the community and goes on with executing his initial idea of taking away all the blocks. In this process, however, he tries things out until he discovers the solution, i.e. he keeps on clicking until he is able to leave the correct number of blocks on the ground and complete the task (Figure 7.12).

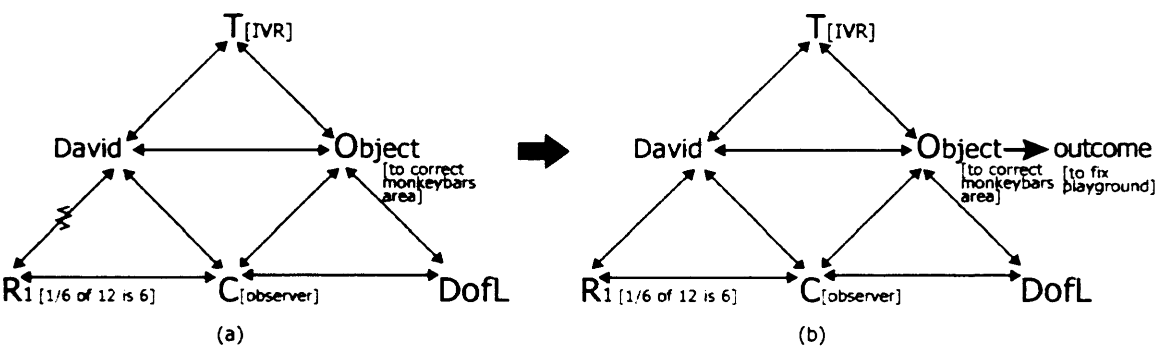


Figure 7.12: An activity system illustrating in (a) the contradiction, with a break between David and R_1, and in (b) the resolution which allowed David to reach his goal without revising his rules R_1.

His actions are performed with great skill and confidence in navigating to and from the pool and picking/placing blocks, a result of his experience in playing computer games, as he himself reported later in the interview when asked how he was able to complete the tasks ("not because of fractions but because of computer games"). His confidence in using the tool suggests that he reverts to that method of solving a problem which he knows that he is good at rather than the conceptual process of trying to work out the fractions, which he admits that he is not good at. The tool (the interactive VR environment) was able to support his problem-solving activity but not his conceptualisation. Thus, he was able to get through the VR task and achieve his objective but there is no evidence of revision of his misconceptions. This is also reflected in his post-test scores, which remain low on Question A2 and on similar questions, indicating that his activity in the interactive VR environment made no difference to his conceptual understanding of fractions.

Example 3

Chloe (PVR13-g9), a confident and very talkative 9 year old girl who participated in the passive VR condition, had a similar response to the slide task (which involved increasing the existing area of ten blocks by one fifth). As in Lisa's case, the robot ("Spike") represents the Division of Labour, taking on the necessary operations to complete the required actions. As soon as the blue bird finished presenting the rule for the slide, Chloe began counting aloud in order to direct Spike on what to do:

80. **Chloe**: One two three... one two three four five six seven eight... So it said that it's covered... one fifth... one fifth... is what it's supposed to be.

81. **O.**: It has to be one fifth more of what it is now. So, how many blocks are there now?

82. **Chloe**: Ten.

83. **O.**: Ok. So how many would you add if you were Spike?

84. **Chloe**: Five.

85. **O.**: Spike has started already trying to add blocks. Where would you add those blocks?

86. **Chloe**: There [*showing the row of five tiles near the crawl tunnel*]. Mmm, no... there [*pointing near the footpath*]... mmm no... can you put them on the yellow road?

87. **O.**: I don't know. Well look at Spike and tell me what you think he's doing.

88. **Chloe**: Oh, he's putting it over there [*pointing at the other side of where she was thinking the blocks should go*].

89. **O.**: Ok, so how many blocks does he need to put?

90. **Chloe**: Two.

91. **O.**: You said five before.

92. **Chloe**: No I mean two there [*showing the two tiles where the robot was already putting the first block*].

93. **O.**: So finally how many blocks does he have to put to make this one fifth bigger of what it is?

94. **Chloe**: Five.

95. **O.**: So, he put one already. Where is he putting the second one?

96. **Chloe**: Next to the first one.

97. **O.**: How about the others?

98. **Chloe**: Uhm, down there. Down on the left side [showing the row of five tiles she had shown originally, next to the crawl tunnel]... No, uhm, on that bit [*showing the two tiles on the footpath*]

99. **O.**: How many more does he need to put?

100. **Chloe**: Three.

Meanwhile the robot has finished placing the two blocks and has "clicked" on the red button so the blue blocks turn into a slide.

101. **Chloe**: Oh! So it only needed two.

102. **O.**: Do you know why?

Chloe shakes her head in a 'no' motion. The robot's actions took her by surprise, as up to this point she was certain about her rules. The contradiction between her rules and the robot's rules is illustrated in part (a) of Figure 7.13 as a breakdown between Chloe and the Division of Labour.

103. **O.**: So you don't understand why, do you remember (what had to be done)?

104. **Chloe**: So there's two... [*thinking for a few seconds*]. Ten, so... oh yeah, you have to times it by two to get twenty.

105. **O.**: Twenty?

106. **Chloe**: No I mean divide. Divide ten by two and you get... uhm... five... yeah what he did. No, no divide ten by five and you get... ten by five... two. Yeah, that's what he did.

Chloe worked out the contradiction and was finally able to explain how the number two was derived as the correct answer. This final explanation provides evidence that the contradiction has been resolved.

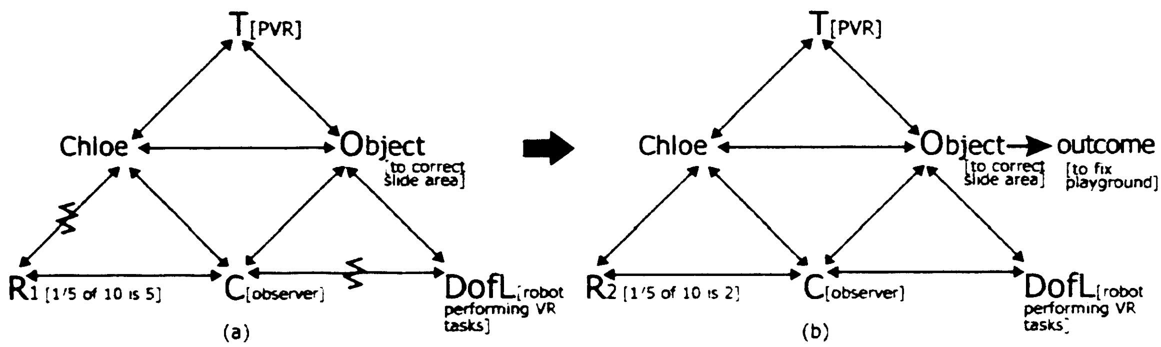


Figure 7.13: An activity system illustrating in (a) the contradiction between Chloe's beliefs (shown as a breakdown between Chloe and R_1) and the beliefs of the community of which the robot is part. In (b) Chloe is able to reassess her model and resolve the contradictions, forming a new rule set R_2 in which ten is divided by 5.

As Kuuti (Kuuti, 1996) notes, initially each operation is a conscious action, consisting of orientation, i.e. planning in the consciousness by using a model, and execution phases. When, however, the corresponding model is good enough or the action has been practiced long enough, the orientation phase will fade and the action will be collapsed into an operation. Indeed, in Chloe's case, a phase of conscious planning took place when she was originally asked to identify how many blocks she would add to the slide area if she were Spike. An execution phase followed where she showed where she would place the five blocks she had identified as being the correct answer for fixing the slide area. However, when Spike completed the slide area correctly by placing only two blocks, a contradiction occurred between Spike's action and Chloe's model, or, more precisely, between Chloe's beliefs and the rules of the community of which the robot is part (Figure 7.13). Additionally, her belief about her purpose in the community (to correct the slide area of the playground by guiding the robot) is shown to be inconsistent when the robot essentially "ignores" it. Upon realisation of this contradiction (line 101), Chloe had to question her model and drastically change it as it proved to be incorrect. Using a kind of "backward thinking" process to explain why the correct answer was such and resolve the contradiction, she came up with a new model (in which the original number of blocks is divided by the denominator) that could later be generalised. In fact, in the next task, which was to compare the two fractions (one third and one fourth) for increasing the area of the swings, she used her newly constructed model to come up with a correct response immediately. The form of her explanation of how the correct answer was derived indicates that the previous action, division, has become fluent, turning into an operation. This is evidence of transfer of acquired knowledge to a new situation.

[*The red bird tells the rule, which is to increase the swings area, now consisting of twelve blocks, by one third or one fourth, whichever gives more blocks*].

107. **Chloe**: One, two, three, four... [*counting the blocks of the swings*] ...twelve. So did she [*the red bird*] say one fourth?

108. **O.**: She said one third or one fourth, whichever gives you more blocks.

109. **Chloe**: One third [*with certainty*].

110. **O.**: How many blocks does that give you?

111. **Chloe**: Four.

112. **O.**: So how did you find that?

113. **Chloe**: Twelve divided by three.

114. **O.**: And how much does one fourth give you?

115. **Chloe**: One fourth... uhm, three...

116. **O.**: Ok, so between the two which gives you more blocks?

117. **Chloe**: One third... yeah.

As the orientation phase is clear right away, the observer continues by asking about the execution phase:

118. **O.**: Where are you going to put those four blocks?

119. **Chloe**: At the end. There [*showing corner by fence*].

The robot, however, is moving to the other side, near the pool. Chloe observes his movement and changes her mind.

120. **Chloe**: No, there [*showing where the robot had already placed the first block*]. There, and then there, and one there and there.

The robot has placed all four blocks and is ready to click on the red button.

121. **O.**: Is that right?

122. **Chloe**: Yes.

123. **O.**: So that's what you would do?

124. **Chloe**: Yeah.

125. **O.**: Ok. If he clicks on his red button... Let's see.

126. **Chloe**: Yeah. [*in a confirmational rather than surprised tone of voice*]

According to Kuuti, this kind of action-operation dynamic is a fundamentally typical feature of human development. For an individual to become more skilled in something, operations must be developed so that someone's scope of actions can become broader as the execution itself becomes more fluent

(Kuuti, 1996). These shifts in conscious attention from operations to actions allow for the reinterpretation of a situation in which objects become what Winograd and Flores (1986) refer to as "ready-at-hand".

Indeed, Chloe's activity system (Figure 7.14) in this case presents a contradiction only in the execution phase, which is quickly resolved when observing the robot's activity. Her reaching the object of the activity and eventually the outcome is evidence of conceptual change that is a result of her acquisition of the rules of the community through a division of labour. Furthermore, Chloe's performance in the post-test supports this evidence, as her post-test scores were improved over the pre-test scores on both problems of ordering fractions and dividing the correct numbers (i.e. finding the fraction of a number without using the denominator as the response).

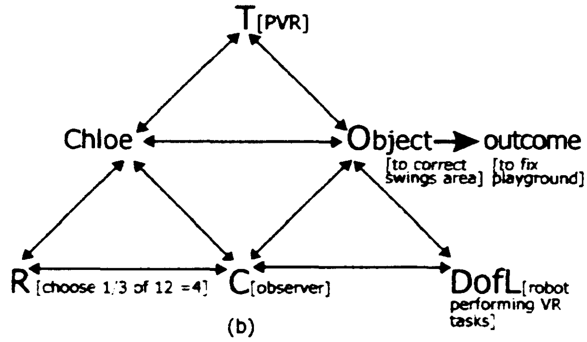


Figure 7.14: An activity system illustrating Chloe's understanding of the Rules, where no contradictions exist.

7.4 Discussion

This section discusses the results of the qualitative analysis, presented in Section 7.3. The analysis began by examining affective issues, i.e. participants' motivation and enjoyment, as potentially intertwined dimensions of activity that could relate to interactivity and learning. Participant responses to the interviews and their observed behaviour indicated that all three of the study experiences (IVR, PVR, and LEGO) were highly enjoyed and intrinsically motivating. However, the non-VR experience lacked the expected reward structure that was embedded in the VR experiences, as the nature of the system (LEGO bricks) had no way of providing the participant with feedback on the task. The absence of this form of extrinsic motivation from the non-VR activity could have an important delimiting effect, since students were not able to know if their actions were correct and, consequently, to reflect on their activity and learning process; however, the methods to measure such situations and the constraints that they may carry with them were not adequate, thus concrete conclusions about how these elements relate to interactivity and learning in the VEs could not be made.

The qualitative analysis went on to describe the general themes identified from the observation and interview transcripts. Two themes, which corresponded to two different learning problems with fractions, were presented with examples of cases from the IVR and PVR conditions. The use of the analytical framework of Activity Theory provided the lens through which the critical incidents and internal contradictions - conflicts that required further attention were identified as possible indications of conceptual change. The importance of contradictions to Activity Theory is that they serve as "functions of a growing and expanding activity system", in other words, as indications of both discordance and, more positively, potential opportunities for intervention and improvement (Barab et al., 2003).

Indeed, what is evident from the examples is that the representational cues of the virtual environment, coupled with the interactive VR system's feedback mechanism, supported a certain type of activity and response which aided in problem-solving. The representational cues acted as visual forms of feedback for the participant, for example, judging if the area is a proper shape (Annie) or guessing the number of blocks based on the available tiles and the surrounding space. Both cues and feedback created contradictions and then opportunities to predict contradictions. In this sense, the interactive VR environment was very successful in supporting problem solving through a trial-and-error evolution strategy; consequently all participants in the IVR study were able to complete all the tasks.

The above examples indicate that interactivity is well suited in facilitating the operations level, i.e. aiding the participant in achieving the tasks by providing tools for successful planning and problem solving. The question posed by this research, however, is whether the interactive properties of a VE, e.g. system feedback, can enable the transformation from conscious actions into operations, where planning and problem solving will have faded from the consciousness to give way to conceptual understanding.

As evidenced through the examples, the passive or guided VR condition provided the ability to reflect on the actions within the VE and try to make sense of the robot's activity. The robot acted as an additional level of mediation which, however, seemed in some cases to support the children's reflective thought, the ability to step back and consider a situation critically and analytically, with growing awareness of their own learning process. This finding agrees with the Vygotskian view that learning environments should involve guided interaction, permitting children to reflect on inconsistency and to change their conceptions (Vygotsky, 1986). Similarly, Smith et al. (1993) argue that the shift from particular conceptions to more complex conceptual knowledge is a process relying on gradually linking ideas to other ideas in new ways. Davis (1998) adds that giving students ample opportunities to reflect and identify where those links can be made (in the context of supportive learning environments) appears important in encouraging integrated conceptual understanding.

Vygotsky also talked about the social context of learning through interaction with peers. Children often play or study in pairs or groups, helping each other in the process. The IVR and LEGO experiences were individual experiences in which the child was alone interacting only with the system and, unavoidably, with the observer of the study. Examples from both the exploratory (Chapter 4) and this main study point to the importance and influence of the probing observer in unintentionally guiding the participants' sense making. However, as noted in Chapter 4, identifying the effect of this kind of interaction was not within the goals of the research. In the case of the PVR, the robot assumed a similar role of an implicit probing entity embedded in the environment, albeit one with no conversational capabilities. Although no verbal exchange was or could be established between the child and the robot, the relationship between them (established through the child's careful observation of the robot's actions) took on a form of cooperation with a teacher or more able peer. In this case, the robot acts as a cognitive tool, guiding and supporting the novice as he or she observes complex tasks, by emulating processes and behaviors typical of an expert. Hence, the role of the robot is considered as one of a partner in the learner's construction of meaning -a cognitive tool to be used to facilitate cognitive processes and thereby help build understanding. Effectively, the robot is creating a Zone of Proximal Development taking the role of an able peer whose actions served to support problem solving, while at the same time providing the participant with the opportunity to think and reflect.

A similar interpretation can be derived from Kahn's observations of children watching a demo versus engaging in free exploration. Kahn (1999) points out that a child watching a demo may be thinking very hard about what she is watching. On the other hand, a child engaging in free exploration may be randomly clicking on things without much thinking. "Some children prefer to understand and plan before attempting to build things, while others like to intertwine planning, testing, building, and revising," he notes. This was certainly the case with David, whose computer gaming abilities seemed to dominate his style of problem solving. The interactive VE was able to support this kind of trying out, planning, and constructing without the participant facing the risk of failure.

The passive VR condition's support for reflection proved to be the most unexpected finding of this analysis. The importance of reflection as a mechanism for conceptual learning is widely recognised. Reflection has been considered integral to learning by a number of scholars. Daudelin (1996) defines reflection as the process of stepping back from an experience to ponder, carefully and persistently, its meaning to the self through the development of inferences. "Learning", he argues, "is the creation of meaning from past or current events that serves as a guide for future behaviour". In the PVR case, the participant was required, both implicitly (by the robot through a division of labour) and explicitly (asked by the observer), to step back and try to make meaning out of the robot's actions. The instances that challenged participants' prior misconceptions to emerge were triggered by the contradictions or breakdowns between their beliefs and the beliefs of the community. In essence, this community, a social structure represented by the robot and the observer, showed to influence the participant's "active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it" (Dewey, 1933). The examples presented of participants in the PVR condition provide evidence of this, whilst there were no comparable examples of conceptual change in the IVR condition. On the basis of this evidence, the PVR condition supports conceptual change which differs in that it is sustained (as in the example of Chloe).

The pace with which this process of reflective thinking took place is reminiscent of the theory of *reflection-in-action* by Schōn (1987). Reflection-in-action, sometimes described as 'thinking on our feet', involves looking to our experiences and attending to our theories in use. It entails building new understandings to inform our actions in the situation that is unfolding. However, when time is extremely short, decisions have to be rapid and the scope for reflection-in-action can be limited. Schōn connects this to *reflection-on-action* which is done later, after the encounter. The act of reflecting-on-action enables the individual to spend time exploring why she acted as she did, what was happening and so on. In so doing, sets of questions and ideas about ones activities and practice are developed. This process of reflection-on-action can be also seen as a kind of metacognition. It is the radical constructivist approach that defines reflection in metacognitive terms, arguing that evidence of learning resulting from reflection is most often supplied by the learners themselves. The importance of reflection in conceptual development has been highlighted by von Glasersfeld who views it as the ability of the mind to observe its own operations. He argues for establishing a sort of metacognitive reflection as the primary goal of instruction: "the primary goal of mathematics instruction has to be the student's conscious understanding of what he or she is doing and why it is being done" (von Glasersfeld, 1984).

The question which remains is how this reflective practice is to be initiated and enacted by the student in the context of an interactive VE. In the case of the PVR experience, the robot acts as a probe for structuring reflection. It creates the setting for what Schōn (1987) calls a *reflective practicum* in which participant and robot 'act' and learn by doing together, even though the participant doesn't act kinaesthetically and the robot has not been designed to learn (at least not in this virtual environment). In this sense, the virtual environment represents the world of practice, while interactivity takes place within an environment that has the potential to provide a reciprocal form of reflection-in-action between the learner and the system, whether this is realised as an autonomous agent or as simpler manifestations of system feedback. In this sense, the passive, or guided, VR environment can be considered as the combination of interactivity (albeit not first-hand) and reflective support with a social constructivist approach.

Finally, individual styles and differences also came into play in this study. As Kahn (1999), children differ in the degree to which they are motivated and effective at exploring on their own or with an animated guide. Some children are timid and will explore only if coached or guided while others are impatient to jump in and explore and try things themselves. Even the same child may prefer different styles of interaction depending upon her prior experience with the software. Ideally a virtual environment should be designed so that a wide variety of children might enjoy and benefit from it, and the combination of interactive and guided activity may be the platform to support this.

7.5 Summary

In this chapter, the data collected from the three conditions of the main experiment (the interactive VR, the passive VR, and the non-VR conditions, presented in Section 6.1.1) was described and analysed. Selected results were presented, first in terms of their quantitative relationships (Section 7.2) and then qualitatively, with the use of the Activity Theory structure. The quantitative analysis examined two response variables, *postcorrect* and *postattempt*, and found strong positive associations with *precorrect* and *preattempt* respectively. Independently, the experimental condition, as well as explanatory variables such as gender and computer and gaming experience, did not have a significant effect on participants' performance in the post-test. On the other hand, a significant interaction effect was found between condition and *precorrect* on *postcorrect*. The VR (IVR and PVR) conditions did not differ between them in terms of their effect of *postcorrect*, but they did differ from the non-VR condition in that they showed slightly better gains.

The qualitative analysis was able to expand on the results of the quantitative analysis by examining the relationships between the participant, the tool, and the learning objective in further detail. The qualitative analysis was structured thematically, with themes that emerged from children's activity and reaction to groups of learning problems, namely the problems of ordering fractions and of using the denominator of a fraction as the answer to a problem. Individual sections, or instances, where interesting contradictions occurred, were identified and related to other measures, mainly to participants' recall of activity during interview discussions and their scores on the tests. Overall, the examples that were presented suggested that the interactive VE supported a process of trial and error which eventually led to successful problem solving activity. The actions based on visual cues (e.g., getting the shape of the area right) or on the feedback provided by the virtual environment (e.g., taking into account the restrictions in placing the blocks on certain tiles) helped most students complete the tasks successfully. However, this did not always show to be tied to their understanding of the underlying concept, nor did it demonstrate proof of fundamental conceptual change. On the other hand, the passive VR condition proved to be surprisingly interesting; in addition to providing the same representational cues and feedback as the interactive VE (only not directly operated by the participant but by a virtual robot), it also fostered a certain kind of reflective process. All of the children who participated in the passive VR condition enjoyed watching and verbally directing the robot in performing the tasks. After completion of each action, each participant was prompted by the observer to explain what the robot had done and why. For the children who had difficulties with the tasks, the robot seemed to take on the role of a more able peer, essentially demonstrating the correct answer. In this sense, the passive VR condition provided, implicitly, a guided form of experience where the learner embarked in a process of reflective observation (of watching others and developing observation about own experience), which, in turn, led in some cases to sustained conceptual change .

Chapter 8

Conclusion

At present, immersive virtual reality learning environments for children are primarily being designed and developed within research settings or by the leisure-based industry for entertainment purposes. However, the growing sense of the educative function of informal educational institutions, such as museums and science centres, juxtaposed with the commercial pressure of competing with other venues for visitors' free time, has lead such institutions to consider virtual reality as a necessary component in their arsenal of tools to educate and entertain. Moreover, since these educational contexts place emphasis on situated and constructivist forms of learning, interactive virtual reality exhibits provide promising platforms for delivering such learning activities and experiences. Hence, their adoption by informal educational institutions is becoming more commonplace, thus also advancing the development of VR systems and applications with respect to their vividness of representation and interactive capabilities.

Nevertheless, research into the effectiveness of interactivity in these virtual learning environments is still in its infancy. This thesis has, thus, focused on interactivity in immersive virtual learning environments and its effect on conceptual learning. The research has addressed the issue through the design of a set of interactive virtual environments and experiments (presented in Chapters 4 through 6) to evaluate children's behaviour in virtual reality. This chapter summarises the empirical work that was carried out for this research as well as the main findings: Section 8.1 revisits and extends the contributions that were presented at the beginning of the thesis; and Section 8.2 presents the limitations of the research and discusses future work directions.

8.0.1 Summary of empirical work and findings

Two studies were developed for the purposes of this research, an exploratory study concerning the construction of ancient columns from their parts and a subsequent main study concerning the redesign of a playground using fractions.

8.0.1.1 Exploratory experiment on learning about columns

For the first study, a learning activity which involved the construction of ancient columns in virtual reality through the placement and manipulation of their parts, was designed and tested with four children. The goal was for the children to learn about the architectural characteristics and differences of ancient Greek columns and to understand the importance of scale and symmetry. The design of interactivity into the virtual environment took the form of minimal and subtle cues that were provided to the participant by the system, such as the fact that the system prevented each column's base from being moved.

The qualitative analysis structured the incidents caused by the users' interaction with the system into different kinds of learning, ranging from simple tool mastery to children's acquisition of concepts concerning acceptable column construction. The analysis illustrated that the exploratory study was limited in providing enough evidence of the latter kind of learning, i.e. of conceptual change. Although the construction of columns did include problem-solving activity, the intended learning goal or the inferred "learning problem" of understanding the differences between columns, remained unclear. Nonetheless, the incidents described showed evidence of some kind of learning, albeit, in most cases, it was not learning that resulted from interaction with the VR system alone.

Additionally, during this first study but also from the pilot study of the main experiment, a number of methodological and practical issues emerged related to the challenges of designing and evaluating an interactive virtual environment for and with children.

8.0.1.2 Main experiment on learning fractions

For the main study, an experiment where children were required to complete tasks that were designed as arithmetical fraction problems was developed. Fifty children participated in the study, in a between-groups design with three different conditions that attempted to cover the different combinations of activity, interactivity and immersion (i.e. an interactive and immersive condition, a non-interactive but immersive condition, and an active but not interactive nor immersive condition). The design of interactivity into the virtual environment covered explorative, manipulative and contributive levels of control over the system, as well as a variety of system feedback in the form of visual and audio cues and prompts provided to the participant.

The focus of the main study was to capture instances of learning that were triggered by interactive activity in the virtual environment and which showed to lead to conceptual understanding of fractions. To identify these instances of conceptual learning a number of measures were taken to ensure that the data collected would result in a wealth of information, which could be meaningfully combined and analysed. Therefore, multiple different methods of testing were designed, ranging from the quantifiable pre- and post- questionnaires to the more qualitative observations and interviews.

The main findings from the quantitative analysis indicated that children in the interactive and passive VR conditions showed to improve their performance on the post-test in comparison to children that participated in the non-VR condition. When examining further each child's activity and reaction to individual problems with the qualitative analysis, instances where interesting contradictions had occurred, emerged. The results suggest that the actions based on the implicit cues (e.g., getting the shape of the area right) or on the feedback provided by the virtual environment (e.g., restrictions in placing the blocks on certain tiles or visual and audio prompts indicating an incomplete area) helped most children in problem-solving and consequently completing the tasks successfully. However, this did not always show to relate to their understanding of the underlying concept, nor did it demonstrate proof of lasting conceptual change.

8.1 Main Contributions

This thesis has made both methodological and substantive contributions. The methodological contributions concern the development of a framework for studying, describing, and analysing the relationship between interactivity, the learner, and the learning objective. The substantive contributions consist of empirical findings concerning the effect of interactivity on children's learning. In Chapter 1, a summary of these contributions was presented; in this section, the contributions will be revisited, stating in more detail how each of the expected outcomes has been achieved.

In addition to the methodological contributions and the empirical findings, a contribution of this thesis has been the critical analysis of the literature concerning a broad problem domain, that of the educational importance and use of interactivity in digital media at large, and VR in particular. The first part of this thesis (Chapter 2) involved the critical examination of the literature in various interrelated fields, from educational technology used within formal education contexts to informal learning and museum-based environments. Interactivity was defined in a holistic manner, by bringing together the different areas and contexts within which it is used. This multifaceted analysis of the literature in the different fields and disciplines not only outlined the current status in these fields and provided an insight into the topic, but, most importantly, identified problems and neglected topics of research, contributing to the overall knowledge of a specific yet increasingly important property of digital technology.

8.1.1 Methodological contributions

Given the gaps identified from the critical literature review, the research has sought to provide a theoretically adequate and empirically grounded study of the role of interactivity in virtual environments for learning. This goal was approached by defining a methodology that could develop the explanatory power necessary to describe and analyse the complex relationships between the elements of the study.

No framework was found in the literature that could describe the complex relationship between the user acting within an immersive virtual environment and the tool, when the objective is conceptual learning. This research has thus suggested a foundation for evaluating students' processes of learning within VEs by applying a descriptive method of interpretation that has not been used before to analyse activity in immersive virtual reality environments. This methodological framework is presented in Chapter 3. The approach involves a mixed method for studying young users' activity in VR, where quantitative and qualitative analyses can complement each other to capture the dynamic nature of the problem and its effect on learning. The use of Activity Theory as an analytical tool was considered central to identifying and describing this contextual nature of the activity. Typically, Activity Theory is applied to the design of systems rather than as a framework to guide evaluation. This research has adapted, developed further, piloted, and refined Activity Theory for the evaluation of learning in the context of immersive virtual reality, thus suggesting a relatively unexplored method of describing and analysing interaction in virtual environments. It, therefore, contributes to extending the application of Activity Theory to activity within Virtual Environments, and evolving its use.

8.1.2 Substantive contributions

Empirical work in the form of an exploratory study and a large evaluation study was carried out to examine the effect of interactivity on children's problem solving, and to identify the critical incidents that occurred as a result of system feedback. The exploratory study served as a test bed for the methodology. The main study sought to identify whether an interactive VR experience can have an effect on conceptual learning in comparison to a passive VR or a non-VR experience. The quantitative analysis of the test scores, using the standard statistical method of logistic regression, showed that participants in the VR environments had a greater overall gain than the ones that did not perform the activity in VR. What is positive about the statistical analysis is that it was able to produce such a result despite the fact that the quantitative research methodology was not expected or meant to form a major part of the experimental design for this research.

Nevertheless, the quantitative analysis was able to address the research question only at the surface level, rather than go into depth to facilitate the interpretation of participants' activity and meaning-making. For this, an in-depth qualitative analysis was performed in order to amplify and throw light on the statistical findings. The findings from the qualitative analysis indicated that the VR experiences were instrumental in maintaining high motivation and focus and that between the interactive and the passive VR, it was the passive that seemed to foster a reflective process within the learner.

Specifically, the children that performed learning tasks in the interactive VE were able to complete the tasks successfully, aided by the cues and feedback mechanisms that were embedded in the design of the environment. This feedback was able to challenge participants' conceptions and create opportunities for resolution of prior misconceptions that emerged. As the interactive VR environment provided the participant with first-person exploration and manipulation capabilities, it was able to stimulate and maintain a continuous engagement in action. In many cases, this enhanced impetus for action aided in problem-solving by trial-and-error, consequently diverting the participant's attention and focus from reflection upon the underlying conceptual learning problems. The passive VR environment, on the other hand, provided evidence of sustained conceptual change through opportunities for reflection. This indicates that the passive VR environment could create a setting for both high- and low-ability students.

From these findings, directions can be provided for future research work and guidelines on the design and development of user interfaces and interaction methodologies that cater to learners and support meaningful learning experiences. The understanding of how humans interact in immersive virtual environments can aid the broader interaction design community and practitioners of interactive VEs in designing and engineering interactivity for training and formal or informal educational systems and contexts.

A technical contribution has been the creation of the virtual environments, initially designed and implemented for the purpose of evaluating the research questions of this thesis. The Virtual Playground application is a stand-alone virtual reality application developed with standard software for CAVE application development as well as with open source application development methods. The advantage is that the final environment could be experienced both with high-end virtual reality equipment (CAVEs) and with low-cost desktop computers and simulators. An additional advantage is that the software could be converted relatively easily into an educational technology application for learning fractions, which would run on normal personal computers.

8.2 Limitations and Directions for Further Work

Several limitations were encountered in the course of this research. Overcoming these limitations provides the first step for further work. Hence, several possible future directions that could be pursued on an empirical, methodological, and practical level have grown out of these limitations and are presented below.

8.2.1 Further empirical work

Further directions for this research on an empirical level involve informing theories, methods or tools on the following themes.

Study more parameters and over time

There have been inherent limitations to the experimental design of the studies due to the need to strictly define and isolate, as much as possible, the parameter of interactivity. In an immersive, multi-sensory medium such as the one used for this research, a comprehensive study of the impact of a single parameter on learning is difficult to conduct because of the large number of variables involved, many of which cannot be easily controlled (such as excitement and the novelty effect).

A main direction for further work would be to carry out longitudinal studies that examine the effect of interactivity in VR over the long term and with regards to other parameters that come into play, such as presence and body movement. Learning is conceived to be a gradual process that can not be studied in a brief experience, no matter how powerful that experience may be. Researchers studying the effect of informal interactive exhibits on learning (Ritterfeld et al., 2004) confirm that "even a highly attractive and stimulating show lasting 20 minutes won't lead to fundamental changes in a student's learning experience". Learning has to be embedded in a broader context and the interactive experience itself should be embedded in a much more extended learning process, where already acquired knowledge can be applied to new problems, exercised in new contexts, expanded or corrected, and students become motivated to seek further information. This means that perhaps a broader examination of interactivity in a VE, in relation to other elements and contexts, may be required.

Study more forms of representation of abstract problems in VR and transfer between representations as a result of interactivity

The focus on interactivity limited the opportunities to study different representations of the learning problem in VR. As VR affords opportunities for multiple representations of reality, the virtual learning environment could be designed to incorporate different forms of visual and audio representation, alternative views and a variety of "magical" features.

A direction for future research would thus be to experiment on the effect of different forms of representation, in conjunction with interactivity, on learning, and issues concerning transfer of learning between representations and activity. Moher et al. (1999) argue that "VR is good at delivering multiple, even believable, representations, and in so doing, seems an attractive medium for displacement learning strategies. If the representations used are too far from the target domain, however, they run the risk of being viewed as a separate reality".

Develop further the methodological framework and issue recommendations for its use in evaluating interaction in VR at large

On the methodological front, difficulties were encountered in the use of a specific framework for the study of the research problem, since very few evaluation frameworks exist to guide the evaluation of learning in virtual environments. Furthermore, the chosen framework of Activity Theory has not been widely and concretely applied to the evaluation of VLEs, with the exception of Barab et al. (1999, 2002) who used AT to study student activity in building a VRML model of the solar system in the context of their classroom. Hence, very few examples existed to draw from when designing the methodological directions for this research. Barab et al. (2003) acknowledge that there is currently no accepted methodology for utilising concepts and principles from Activity Theory and that what is offered is at best a loose heuristic for use.

A direction of further work could involve the continuation of the development and refinement of this descriptive framework. It would be interesting to explore and further develop the methods of Activity Theory as an explanatory tool for analysing activity within virtual environments for both education and training.

Improve the conditions and methods for studying VEs for children and with children

On a practical experimental level, one of the main problems faced with in the empirical work concerned the technology and technical failures of the apparatus, especially of the wireless head tracking system used in the CAVE, which operated inconsistently. Thus, the tethered head tracker had to be used with some of the participants, meaning that these users had to endure wearing a heavier device and one extra cable. The solution found for this was to use a special cap that was able to hold the tracker without applying all of its weight directly onto the user's forehead. However, the issues concerning the suitability of the apparatus for children remain. As the CAVE peripherals are not made for different head sizes, especially for smaller heads, they continue to be rather heavy and obtrusive, despite this technology having been around for almost fifteen years.

Improving the apparatus and methods of conducting studies with children in immersive virtual environments may sound more of a practical issue to be resolved rather than a research challenge. Whilst there are not many things one can do to correct problems concerning the technology beyond trying to convince the VR industry to correct them, there are perhaps research methods and methodologies in other fields that have developed guidelines on working with children and that could be transferred and adjusted to immersive virtual reality settings. Such approaches may include participatory design and informant design methods (Scaife and Rogers, 2001), which would be worth looking into.

Examine interactivity within the context of multimodal interfaces

Technological limitations and practical issues surrounding virtual reality interfaces, especially the head and hand tracking system used in this research but also the hand-held interaction device, as common as they may be, determine the widespread use of this technology in public spaces. Indeed, museums that operate VR exhibits that are open to the public face such issues on a daily basis (Roussou, 1999).

Recent developments on intelligent user interfaces, in the emergent field of Ambient Intelligence, focus on enabling users to control and interact with the environment in a natural (voice, gestures) and personalised way (preferences, context). These developments have already started converging with virtual reality research projects, especially in the newer areas of Mixed Reality and Augmented Reality, by integrating sensors, computer vision, natural language understanding, haptic interfaces, etc. in virtual reality installations. The goal of these multimodal interfaces is to ultimately enable users to interact with computers using everyday skills, therefore they are increasingly found in leisure-based applications of virtual reality technology. Given the rapidly evolving research in this direction, there is ground for future work on what concerns interactivity in relation to these other, more natural forms of interaction in VR and their benefit for education. Kaur (1998) in his thesis on VEs and usability suggested that his theory of interaction would benefit from "evaluation in a wider range of contexts, particularly with different application types and interaction styles (e.g., gestural), and with immersive VEs and expert users". Indeed, the exploration of other forms of interaction, such as gestural or haptic interfaces, speech recognition, even the triggering of olfactory responses, where applicable to learning, would benefit the examination of the potential of multimodal immersive virtual environments for education.

Provide recommendations on the design of interactivity for learning in virtual environments

Based on the findings of this research, guidelines and research-based recommendations can be compiled concerning the design of interactivity from a technical, cognitive, affective, and pedagogical perspective. For example, detailed design paradigms for an educational VR environment could incorporate pedagogical guidelines that synthesise both a constructivist and a guided instructional approach. A practical design recommendation could involve harnessing the motivational power of interactivity to engage the participant in action, which would then be coupled with support for reflection. This dual prompting (prompts for action and prompts for reflection) could be embedded in the same VE in a variety of forms, ranging from audio and visual feedback to the use of intelligent agents and storytelling mechanisms (Figure 8.1) for vicarious action. This use of "layers of prompts" could be leveraged by other projects and could have an effect on future application design in which different levels are designed, similarly to the discursive, adaptive, interactive and reflective conversational framework proposed by Laurillard (2002).

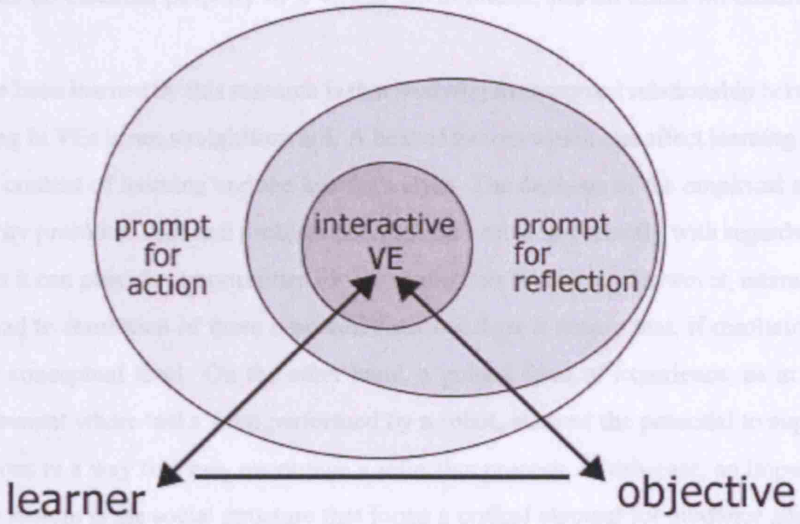


Figure 8.1: Virtual environments that act as mediators between the learner and the learning objective can be designed to support the learning process with multiple different levels of interactivity.

8.2.2 Further development and adaptations of the Virtual Playground

As far as the Virtual Playground application is concerned, there is still room for a number of usability improvements. Many ideas for further development and exploitation are also under consideration, most of which will be actively pursued in the near future. The Virtual Playground was designed specifically for the purposes of this study, thus it incorporates tasks that are designed for evaluation and not directly for instructional purposes, *per se*. With the necessary adjustments to the storyline, scenario, and the tasks, the Virtual Playground could easily become an engaging instructional environment in the form of an educational game. This would require incorporating further design criteria and research findings regarding the design of educational games for mathematical learning in order to make the concepts more explicit. Some of the educators that collaborated in the initial phases of the design have expressed interest in having a tool such as the Virtual Playground for use in their classrooms. Steps towards practical application of the environment have also been taken through contact with educational organisations involved in public programmes and funding initiatives for the penetration of technology in education. Contacts with large institutions, such as the BBC, the NESTA Future Lab, and museums, were made throughout the course of the research. These institutions are actively exploring the use of virtual, mixed, and augmented reality in education and consider interactivity to be at the core of their interests for future work. Their concerns on how to best design interactivity for learning can be informed by this research, while new directions for its continuation may be proposed.

8.3 Concluding Remarks

The central theme of this thesis has been to investigate user interaction in virtual environments, focusing on the role of interactivity in virtual reality on learning. The key research question asked whether interactivity, as an essential property of a virtual environment, has an effect on children's conceptual learning.

What has been learned by this research is that studying the assumed relationship between interactivity and learning in VEs is not straightforward. A host of factors which can affect learning come into play, including the context of learning and the learner's style. The analysis of the empirical studies suggests that interactivity promotes skill and problem solving and - most importantly with regards to the research question - that it can provide opportunities for contradictions to emerge. However, interactivity does not necessarily lead to resolution of these contradictions nor does it ensure that, if resolution is made, this will be at the conceptual level. On the other hand, a guided form of experience, as in the case of the virtual environment where tasks were performed by a robot, showed the potential to support resolution of contradictions in a way that may encourage a reflective process. In this case, an important parameter in the activity system is the social structure that forms a critical element for guidance and prompting. In the case of the VEs developed for this research, this social structure was embodied in the robot that led the activity, thus encompassing an implicit instructional role. Additionally, the observer, also part of this social structure, had a positive role on some children's learning, even if unintentionally. What this suggests is that the social structure may be more important than interactivity, on its own, in supporting the process from problem solving to the making of meaning. Yet, in combination, interactivity and guided activity may be a powerful scaffolding tool to support reflection and sustained conceptual understanding.

Overall, the research presented in this thesis, concerning interactivity in an immersive virtual environment and its relation to learning, represents a step in the broader context of learning within immersive, interactive, experiential digital environments. Further study on a long-term basis is required to examine the elements that comprise the complex relationship between the learner, the digital tool (in this case a virtual environment) and the learning objective, and, ultimately, to acquire a deeper understanding of what constitutes learning within virtual environments.

Appendix A

Exploratory Study: Detailed description of participants' activity within the VE

The exploratory study took place in May and June 2003 with three participants. All sessions were recorded on video. An overview of each session has been extracted from the three-hour video footage and is described below.

A.1 S1: Lidia (EXP01-g8)

Lidia is a good student -she is almost 8 years old and in Year 2 in school. She has not experienced a virtual environment before but she plays computer games, games on her parents' mobile telephone, and knows what e-mail is, so she is generally aware and comfortable with technology.

When an image of the 3D model of the Ionic column was shown to her on paper, she did not know how to call it but she recognised that she had seen it before when visiting the Acropolis and knew that it is something that "holds buildings up". She has not been taught about columns in school and has no specific knowledge of the orders, parts, or differences between columns.

The explanation/demonstration (training) of the functionality of the interface preceded the actual task but was not independent from it, i.e. the subject was free to start with the first task whenever she felt comfortable with the system. This lasted for about 2 minutes and then she began with Task A (the construction of an Ionic column), which lasted for approximately 11 minutes. She began constructing the column immediately when the interface device was given to her, without waiting for the "training phase" to end. However, she spent a considerable amount of time learning the system (for example, handling the idea of proximity to a virtual object in order to pick it up). She had problems remembering that a red bounding box must be displayed around the object she intended to pick and this resulted in many accidental moves of pieces that she had already placed successfully. This was very frustrating to her. Also, most of her time was consumed with trying to align the pieces or just trying to get the pieces one on top of the other, and since there are no physics (to lock the pieces in place, for example) it was difficult to judge if she had gotten it right. Despite these technical problems, she chose the pieces quickly without pausing to think and the task seemed to be a fairly automatic procedure for her. She completed the task but the resulting column was pretty badly aligned (if physics were programmed in it would certainly had fallen). She spent another 2 minutes straightening it as much as possible before she declared that she had finished.

For Task B (the construction of two columns, an Ionic and a Doric), the subject was not told at the outset that she had to construct two columns instead of one, but she inferred this through the fact that there were more pieces in the VE than before and she remembered that the photographs shown to her had two different columns. She started immediately by picking the pieces that were on one side to make the column whose base was located closer to that side (this took about 3 minutes). Then she picked the pieces on the other side to make the other column. She made an Ionic column with 6 pieces (excluding the base) and started creating a Doric with the remaining (4) pieces. At this point she was asked why she chose some pieces over others and she replied that she chose the thicker pieces for one column and the thinner for the other, although it hadn't seemed that she had made a conscious decision. After having said that (and justifying in retrospect how she chose the pieces) she went back and observed her columns more closely and, as a result, corrected her previous work by removing the thicker piece from the Ionic column and putting it in the Doric. To the question why she chose the thicker pieces for one column and the thinner for the other, she replied that one base is thinner and she chose the thin pieces for the thinner base. Despite the above realization, she completed two columns that differed in the number of pieces they had and thus differed in height (the Ionic had 7 pieces and the Doric had 5). She described what she had done in length and, when asked, she identified the differences between the two columns but did not feel that she needed to correct something. After more similar questions, she responded by picking the wrong piece out of the Ionic column and placing it in the Doric.

After a 10-minute break she proceeded with Task C (the construction of an Ionic column where some of the pieces are noticeably smaller or larger than others). She started constructing her column and when asked what she sees she replied immediately that the piece she had picked up was bigger than it should. When asked if she feels she should change its size, she replied that she had already done this (she figured this out by pushing buttons, without knowing that this could be done and without receiving any training). She completed her column in little time by resizing the pieces as much as she thought. Her decisions were based on what "looked right".

Upon completion of each column in each task, the observer was able to see if the pieces were placed in the correct order (the pieces are colour-coded and the colours are revealed with the press of a secret button). For Task C, it didn't make sense to record the order since almost every piece was resized and made to fit.

The fact that the subject did not get the order correct in any of the columns indicates that until the end of the experiment she continued to believe that all of the pieces of each column were the same, so she selected them randomly and did not compare them when constructing her columns.

After completion of all tasks, the subject was asked if she found the tasks to be difficult or simple and to elaborate. She said she found all tasks to be fairly difficult. As she was exhausted, it was hard to get any other meaningful information out of her, so the sessions ended at this point.

Overall, she distinguished between two types of column, but only after the observer's unintentional

	Correct order	TASK A	TASK B		TASK C
			Ionic	Doric	
	Black	black	black	black	black
	Yellow	red	red	blue	green
	Blue	green	blue	yellow	red
	Green	blue	green	red	yellow
	Red	yellow	yellow	green	blue
	Base	base	base	base	base

Figure A.1: The order of the column pieces as recorded after Lidia's tasks

intervention, which made her go back and re-evaluate her actions. In other words, she performed an operation, when asked why she did what she did, she realised that this operation had failed so she re-performed the operation successfully. After the end of the session, when she was asked to explain the difference between two columns, she drew on what she had learned from addressing that failure in order to give her explanation. She seemed to function in this way in more than one instance, i.e. she acted intuitively without paying too much attention to what she did (although she was good at "talking-while-doing"), until the observer prompted for further explanation, at which point she would reflect on her actions.

A.2 S2: Harry (EXP02-b12)

Harry is a very good and organised student in Year 6, and has experienced a virtual environment before in a CAVE environment during a school visit. He plays computer games at his uncle's home but does not have a computer at home and does not use one at/for school. However, he is generally aware and comfortable with technology.

When an image of the 3D model of the Ionic column was shown to him on paper, he recognised it right away. When the 2nd image of the Doric column was shown to him, he responded that this was also a column but of a different type, the first being of Doric order and the 2nd of another type whose name he couldn't remember). He also knew that one is thicker and the other is thinner and that the columns were made of multiple pieces "attached to each other with lead". He has been taught about columns in school as part of his History class.

Training with the interface lasted for about 2 min.

Task A (the construction of an Ionic column) took approximately 16 minutes. He began constructing the column by choosing a piece at random, "because they all looked the same". Quickly he realised that every drum "is different at the top than at its bottom" and began paying close attention to alignment. When he reached the last drum (in about 6minutes) he examined it from all possible directions and realised that it was wider than the drum below it, so he took the column apart and started over again. He spent a considerable amount of time examining each piece before placing it, by turning each piece around in the air, comparing it with the one below it, placing it, taking it off, placing another one and so on. When he was asked why he thinks alignment is important he answered, "because that way the base is more steady". He concluded that finally the size of each piece was different, with the top piece being the thinnest. He completed the task, resulting in a correct and perfectly aligned (as much as the system permitted) column.

Task B (the construction of two columns, an Ionic and a Doric) took approximately 25 minutes. The subject was not told at the outset that he had to construct two columns but when asked what he thinks he is supposed to do, he mentioned that he probably would need to construct two columns because he sees two bases. He started by picking up all the pieces that were on the virtual ground and placing them "in the air", one next to the other. He clearly divided the thin from the wider pieces by placing all the thin (=Ionic) pieces on the left wall (closer to the Doric base) and the thick (=Doric) pieces on the right wall (closer to the Ionic base). In the case of the Doric column, he wasn't sure whether the base was the square flat piece or another piece that looked like it but was more curved (the capital). He solved this when he realised that he couldn't pick up the base but was not able to explain this well. When he started constructing the columns, he rearranged the pieces after comparing and seeing that one belonged on the other side. He completed Task B and the pieces were correctly placed both between the two columns and within each column.

After a 15-minute break he proceeded with Task C (the construction of an Ionic column where some of the pieces are noticeably smaller or larger than others) which also lasted for about 25 minutes. When asked what he notices in this environment, he replied that the capital is really small. Then he noticed that other pieces were different in size too. When he was told how to resize the pieces, he started placing pieces two by two in the air, comparing and resizing them, before placing them on the base. After about 20 minutes, he completed the column, which, however, was too short, so he decided to make all the pieces bigger x3 (except the capital that was enlarged x4). He declared that he had finished although the column still seemed small, but he decided to end it there.

Upon completion of each column in each task, the observer was able to see if the pieces were placed in the correct order (the pieces are colour-coded and the colours are revealed with the press of a secret button). For Task C, it didn't make sense to record the order since every piece was resized and made to fit.

The fact that the subject had the correct order in all cases demonstrates that he had identified that the pieces were different and paid close attention to detail.

After completion of all tasks, the subject was asked if he found the tasks to be difficult or simple and to explain his answer. He found Task C to be the most difficult as well as Task A "until he learned how to handle the system". He also noted that it would've been easier to do this in reality because "you are more sure when you use your hands".

When looking at the printed images again, he noted that he had noticed the different width of the columns in the pictures but didn't realise it until he made the columns. He was asked if he thinks he had learned something and responded that he learned how columns are made. When the observer noted that

	Correct order	TASK A	TASK B		TASK C
			Ionic	doric	
	black	black	black	black	black
	yellow	yellow	yellow	yellow	
	blue	blue	blue	blue	
	green	green	green	green	
	red	red	red	red	
	base	base	base	base	base

Figure A.2: The order of the column pieces as recorded after Harry's tasks

it seemed that he knew this already, he responded that he felt he learned something but could not identify what. He also noted that the columns differed in the following: they were of different order; they had different bases and capitals; one could not put the wider pieces on a column if its base was thinner.

A.3 S3: Paul (EXP03-b9)

Paul is an average student who has just completed Year 3. Like Harry, has experienced a virtual environment before in the CAVE during a school visit. He uses his parents' computer at home to play computer games but does not use it for school. He is generally aware and comfortable with technology.

The image of the 3D model of the Ionic column was shown to him on paper and he was asked if he recognised what it is. He responded that he had seen it on the Acropolis but did not know what it was called. For the Doric column he responded that he had seen it somewhere else and when asked if it was the same as the other column he responded negatively and noted that one column (the Doric) is thicker and the tops and bottoms are different.

Training with the interface lasted less than 1 minute, since the subject picked up the first piece immediately when the joystick was given to him.

Task A (the construction of an Ionic column) lasted approximately 8 minutes. He began putting together the pieces "in the air", starting with a column drum on top of which he placed the capital. When asked why he decided to begin this way he answered that he was trying to make what he saw in the photograph. When asked if he will make his column in the air he answered that "no, I will continue my column until it reaches the ground". After about 5 minutes he had managed to squeeze the last drum under the others and attempted to pick up the base. After realising that the base did not move, he deconstructed the column he had made in the air by starting from the top drum, which he placed at the bottom (directly over the base) and every other piece on top of it until he placed the capital. When asked why he had reversed the order of the pieces, he noted that all the pieces were the same so it didn't matter. Overall, he completed this task in little time without paying any attention to alignment. The resulting column had gaps between the pieces and was not straight. When asked if he believed this column would stand up straight in reality, he answered that it would probably fall. He did not bother to work on making it seem straighter because "it would be difficult" and because this was not reality but "a computer" so it didn't really matter.

Task B (the construction of two columns, an Ionic and a Doric) took approximately 16 minutes. He started first by identifying the base of the Ionic column and saying that this piece didn't move (as he remembered from the previous task). He also identified the base of the Doric column and started constructing that column first because it "seemed simpler to do". He placed the first (bottom) drum and, when searching for the next piece, he picked every other drum from the ground and put it on top of the bottom drum to compare. After about 11 minutes he made two columns, a short Doric and a tall Ionic. He found the wide piece in the Ionic and moved it to the Doric. He then spent a couple minutes trying to straighten the Doric capital. After examining his columns again he made another change, switching two drums between the two columns. He finalised his changes and declared that he was happy with his columns. The resulting columns had the pieces divided correctly between columns but, as with Task A, very little attention was given to the final "look" of the column (if physics were programmed the column would certainly fall).

After a 15-minute break he proceeded with Task C (the construction of an Ionic column where some of the pieces are noticeably smaller or larger than others). He worked on this task for approximately 9 minutes. The first drum he picked up was much wider than the base. Although he identified and pointed out this fact, he continued placing the drum on the base and all other drums one on top of the other. When he finally placed the capital, he noted that it is very small. When asked if he thinks it should be bigger, he answered that this was not necessary and started de-constructing his column. He rearranged the pieces but noted that one drum was much wider than the rest. He had already spent 4 minutes in the task when the observer asked him if he wanted to change its size and, after he said yes, told him how to do so. Once he knew how to resize, he created the column by resizing all the pieces. When asked if he thought the column would stand with a capital that is as large as the one he had made, he said "no, because the capital would be too heavy", however he made no attempt to change anything.

Upon completion of each column in each task, the observer was able to see if the pieces were placed in the correct order (as mentioned, the pieces were colour-coded and the colours were revealed with the press of a secret button). For Task C, whilst for the other subjects it didn't make sense to record the order since every piece was resized and made to fit, in this case the order was written only because it was close to the correct order. However this is attributed to chance.

The fact that the subject did not get the order correct in any of the columns indicates that until the end of the experiment he continued to believe that all the pieces were the same, so he selected them randomly and did not compare them when constructing the columns. In general, throughout all tasks, he made a clear distinction between reality and virtual reality and thus did not bother working on his columns in order for them to look as close to a real column as possible.

After completion of all three tasks, the subject was asked if he found the tasks to be difficult or not and to explain his answer. He answered that he found everything to be easy. With further prompting he revealed that Task B was a bit more difficult for him because he "confused the pieces" between them.

	Correct order	TASK A	TASK B		TASK C
			ionic	doric	
	black	black	black	black	black
	yellow	red	green	yellow	blue
	blue	green	yellow	red	yellow
	green	blue	blue	blue	green
	red	yellow	red	green	red
	base	base	base	base	base

Figure A.3: The order of the column pieces as recorded after Paul's tasks

Nevertheless he "finished the columns correctly" because he "remembered how the columns looked like from the pictures he had seen before the beginning of the tasks".

Appendix B

Design and Software Implementation of the Virtual Playground

The experiments in virtual reality involve participation in two virtual environments, a training environment and the main experimental environment. A description of scripts and design elements for each of these environments follows.

B.1 Training environment

A simple training environment was designed to precede the VP environment experience. The purpose of this VE was to train the user in the use of the joystick for spatial navigation and the buttons for picking/placing and manipulating objects. The duration of the training environment was approximately 3 minutes long.

Upon entering the training environment, the user sees a bright yellow curvy path starting from where s/he is standing and continuing forwards into the virtual space. A virtual white beam is visible as an "extension" of the user's hand into virtual space. Three cubes floating in virtual space can be seen at a distance, at the end of the path.

A voice welcomes the user and explains the task:

> *Hello and welcome to virtual reality! You are holding a magic wand: this is what you will use to move around and do things. Do you see this yellow brick path? Use the joystick, the big middle button on your magic wand, to move forwards on this path.*

If the user does not take any action for a few seconds, then the following sound is heard:

> *Go ahead, try it! Push forward on the middle button. Try to avoid falling off the sides!*

When the user is able to navigate and reach the end of the path, further movement is disabled by the program. The three cubes are now clearly visible and within reach of the user's virtual beam. At this point in the training is where the user will learn to select each one of the three cubes with three different wand buttons. The voice guides the user in this process:

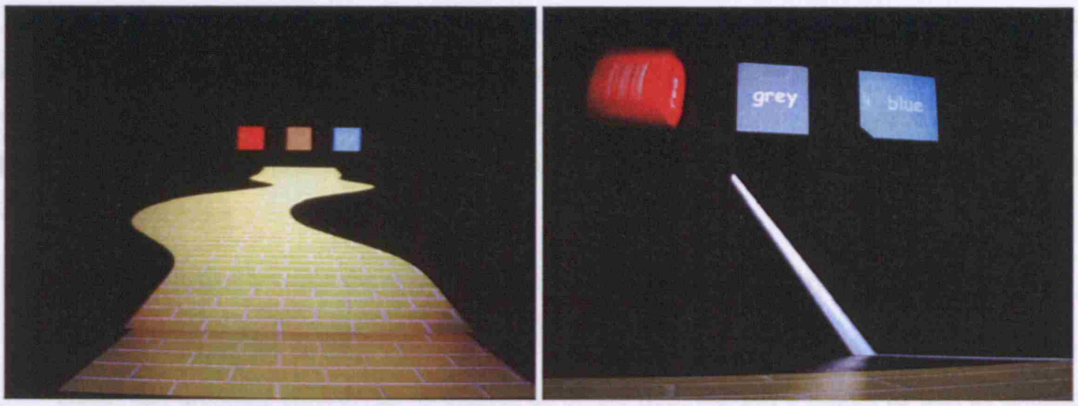


Figure B.1: Views of the training environment.

Great you made it! Now let's learn how to select objects: point your magic wand towards the red cube; when you see the yellow line around it then press the red button once and let it go.

The user must hold up the white beam, which visualizes the vector that extends the user's hand into the virtual space, and point it in the direction of the red cube. When the beam intersects the red cube, then a yellow wireframe bounding box appears. The user must then click on the red button. As a result of clicking, the red cube starts spinning while a "spinning" sound effect provides extra feedback (Figure B.1). The voice continues:

Now point your magic wand towards the blue cube to your right and press the blue button to select it.

The user must act in a similar manner to select the blue cube. The blue cube starts spinning in a different direction than the red cube, while a different sound is heard. The voice is then heard again:

Now do the same with the grey cube, only this time press the big grey button in the middle once and then move your hand around.

The user must click to select the grey cube, which then becomes attached to the beam and can be moved around along with the movement of the user's hand. While this is happening, the voice explains:

The grey cube should be attached to your magic wand! Click once more to let it go!

When the user clicks on the grey button, the grey cube becomes detached and is left floating in space, at the position where the user clicked to let it go. The purpose of this action is to familiarise the user with the interaction metaphor of picking up virtual objects, which then travel along with the user's hand as it moves, and are let go when the user clicks on them. This kind of activity will be performed extensively by the user later, in the Virtual Playground.

Brilliant! You now know all you need to begin your experience in virtual reality.

By the end of this trainer the user should have learned how to navigate and how to select objects in the VE. Also the user should have learned how to grab an object (attach it to their hand and let it go) with the wand. These activities are analogous to what the user will be doing in the main environment of the Virtual Playground. The same three buttons on the wand will be used later during the VP experience for the following tasks:

- Button 1: toggles between the construction mode of the VP and the playground mode.
- Button 2: allows for picking virtual objects (i.e. "attaching" an object to the end of the user's beam) and dropping objects (i.e. detaching an object from the user's beam), as well as selecting the birds to trigger their action.
- Button 3: toggles between perspective or ground view and top or "birds-eye" view.

On an Intersense IS-900 wireless wand, such as the one used in the UCL CAVE, there are five visible buttons, four of which are colour-coded buttons while the fifth is the joystick which doubles as a button (Figure 3.1). For simplicity of instructions and ease of use, the buttons on the wand were re-mapped so that the user only needs to use the front three (top three in Figure 3.1). The colours of the front three buttons (red, dark grey, and blue) correspond to the colours of the cubes in the training environment. The choice of the front three buttons was made following careful usability considerations: the middle button is where the user's thumb usually rests, so this was used both for navigation (it couples as a joystick) and for picking and placing (the main activity). The other two were used to toggle between supportive activities.

B.2 Detailed scenario of the Virtual Playground

Following the training environment, the user is then introduced to the Virtual Playground (VP). The introduction of the VP and the presentation of the tasks to be carried out within it follow a storyline. This was considered necessary for engaging the user in the environment, especially since the VP was to be used with children. Thus, a "scenario" was created and communicated to the user in a narrative form, in some cases explicitly (by telling them) and in other cases intrinsically, within the VE. The goal was to connect the idea of re-designing a new playground to a potentially realistic situation which the children could identify with. Therefore, the children learn that a new playground is being built in their neighbourhood and that the local administration is about to open it to the public. However, as the administrators visit the grounds to inspect the new playground, they notice that the designer responsible for the project has made many mistakes. Everyone is furious: the designer is fired and the local authorities decide to seek the help of a playground user (i.e. the child participant in the study) who must re-design the playground, correcting the original designer's mistakes. The designer's mistakes mostly concern the size and position of the objects in the playground, so the participant must change the size of each object according to the rules that will be provided during the virtual experience. The rules are communicated to the user by virtual characters or else the "good spirits" of the VP, an owl and six birds. The narration was written by the researcher in plain English and was checked by collaborating teachers (as well as by the person acting out the owl) who made detailed suggestions on the most appropriate use of words for the targeted age group (for example, replacing the word 'select' with the word 'choose'). The narrative was then recorded in a studio in digital form and subsequently divided by the researcher into separate audio files, editing parts where necessary.

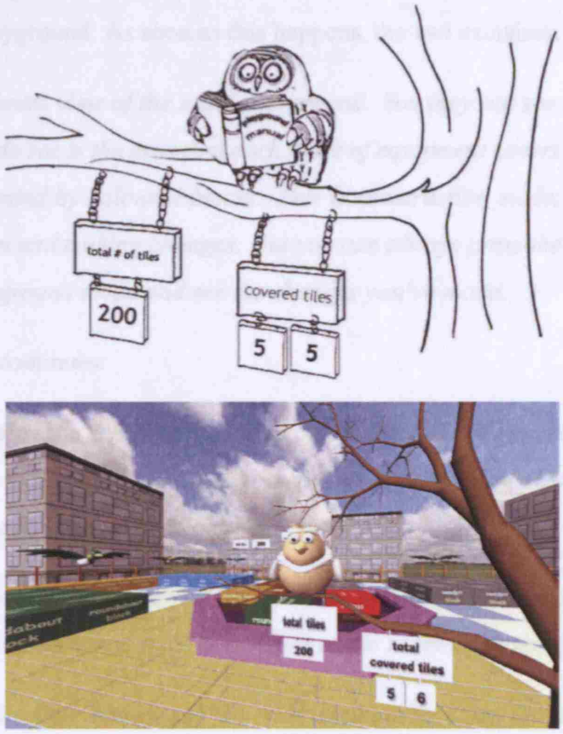


Figure B.2: The sketches of various elements of the Virtual Playground that were made during the design of the concept (top), turned into 3D models and animations (bottom). Here, the owl agent greets the user and provides the overall scenario and instructions on the task. The signs below change dynamically every time the user places or removes a block from the ground, showing the number of covered tiles at any given time.

The owl is the "spirit" of the playground (Figure B.2). The owl seems to "know" everything about the playground and about the rules. When the user has reached the area in front of the tree, the owl will begin to speak:

> *Welcome to the playground! The birdies and I have been waiting for you to help us fix this mess! Look around! Almost everything in here is either too big or too small or not in the right place. You can help us correct this and finally have a nice virtual playground to play in!*

While the owl is speaking, the user is taken on a tour around the playground. The playground elements are greyed out and distorted, to emphasise their undone state.

> *Unfortunately, in my old age, I can't do much myself and I can't hear very well either. But I can give you some tips and tell you the rules, so listen carefully.*

So here we go! First of all, you have to switch to construction mode in order to do some work. Go ahead, click on the red button on your magic wand to test it.

The owl pauses and waits from the user to click on the red button on the wand. When the user clicks on the red button, the playground elements are replaced by the coloured blocks that represent each one's area on the grid of the playground. As soon as this happens, the owl exclaims:

Woo! This is a different view of the same playground. You may not see the play equipment here, but what you do see is the area that each piece of equipment covers on the playground. The area is represented by coloured blocks. This is construction mode; it is the mode that you'll be working in and making changes. But you can always press the same red button to switch back to playground mode and see the changes you've made.

The owl pauses and then continues:

Do you see that pool in the centre of the playground? It's full of different colour blocks that you can use to add to an area in order to increase its size. You can also put blocks back in the pool if you want to make an area smaller.

When you're in construction mode you can see the playground from above as if you were a bird. Click on the blue button to try it now. Click again to return to the ground.

The user clicks on the blue button and the view changes to a top-down view of the playground (Figure 5.8). A "zoom-out" sound effect is heard while the transition from ground-level view to top-down view is made. When clicked again, the view returns to ground view and a "zoom-in" effect sounds to enhance the visual transition. The blue button can be clicked anytime throughout the experience to toggle between the ground view and top-down view.

When the user has returned to the ground after testing the blue button, the owl continues to speak:

Ok, but how will you know what to do for each area? Well, you will have to move close to each birdie and it will tell you what you should do to fix that area. Only areas that have a birdie over them represent play equipment that can be changed. Remember that you have to be in construction mode to make changes to an area but you can always switch back and forth with the red button to review what you have done.

You can make changes in any order you wish. Don't forget though the general rule of the playground: in the end, the total number of tiles that are covered by playground equipment must not be more than a quarter of all the tiles in the playground.

These signs hanging over here and the billboards on the top of that building across there will always show you how many tiles are on the playground and how many you've covered. Remember to check the signs before you finish!

Ready - get set -go!

At this point, navigation is enabled and the user is free to move and start the activity. In the case of the passive VR playground in which the user is just a viewer, this is the moment when the robot appears in front of the user, ready to begin the activity. The robot starts moving toward the nearest bird (the green bird representing the roundabout area) and clicks on it for the rule to be heard. The robot is always positioned two steps ahead of the user. When the robot moves, the user is moved along on the same path, giving the illusion that she is following the robot. This means that the environment as a whole moves, as if the user was using the joystick to navigate. The user can also physically move within the limits of the physical -approximately 3x3- space of the CAVE or look at a different direction than that of the robot; however, the user is always "pulled" into position behind the robot for the duration of the prerecorded activity. This technique, also referred to as "rubberbanding", has been used with virtual guides in virtual heritage productions, where mechanisms to keep the visitor group on track were required in order to control the guided tour[1].

When recording the robot's actions, the robot's pace was defined by the average time needed by the pilot users to complete each task. The total duration of the robot's prerecorded activity is 27 minutes.

B.2.0.1 Birds: the virtual "instruction providers"

Six differently coloured birds are present in the environment and serve as characters that communicate to the user the rule for each area that needs to be changed (Figure B.3). The birds are the characters that present the task to the user, that is, the fractions problem. Each bird corresponds to the playground area of the same colour -the red bird represents the red swings, the blue represents the slide (Figure B.4), and so on. In this way, the rule delivery is distributed, thus providing the flexibility to the user to choose whichever playground element she wishes to start from. When approaching the grey bird, which is located over the sandpit, the user hears:

> *Hi, I am the grey bird. The sandpit is correct - it is the only thing in this playground that does not need to be changed. So it can continue to cover the same amount of space.*

Figure B.3: Six birds represent the six different playground equipment and provide the user with the necessary rules for each.

The blue bird represents the slide area, which needs to be increased. The rule requires that the user compares the current area of the slide to itself.

> *Hello, I'm the blue bird. The slide is smaller than it should be. Its area must be increased by one fifth of the area it covers now. You must decide how to do this!*
>
> [pause] *If you need to hear what I said again, point at me and click on the big middle button.*

[1]Kruijff et al. (2004). Specification of affordable VR systems for Museums. Public deliverable of the DHX (Digital Artistic and Ecological Heritage Exchange - transcontinental Guidance and Exploration in globally shared cultural heritage) project.

The brown bird is located above an area where no blocks are present. This is because it represents the crawl tunnel, which does not exist in the wrong version of the playground. Hence, the necessary brown blocks must be added. The rule requires that the user decides on the area of the crawl tunnel by calculating the fraction of another element (the sandpit).

> *Hi. I am the brown bird. There is no crawl tunnel in this playground. You must add one! The crawl tunnel should be a square. It should cover as much area as one third of the sandpit.*
>
> [pause] *If you need to hear what I said again, point at me and click on the big middle button.*

The green bird represents the roundabout area, which needs to be decreased and moved inward, away from the fence. The latter modification is not explicitly communicated to the user. However, every time a user attempts to add a block next to the fence, the system will provide feedback against it (e.g., "oops, that's too close to the fence"). In this way, the user is expected to understand that something is not correct with the placement of the roundabout. The reaction to such feedback was important to look for in the main study and to examine what properties can be inferred from such implicit feedback.

> *Hello, I'm the green bird. The area for the roundabout is too big. You have to take away blocks to make it smaller. The area must be reduced to one fourth of the area it covers now. Remember that the area must be a square.*
>
> [pause] *If you need to hear what I said again, point at me and click on the big middle button.*

The yellow bird represents the monkey bars, which need to be decreased. The rule requires that the user decides on the area of the monkey bars by calculating the fraction of another element (the sandpit).

> *Hi, I am the yellow bird. The monkey bars are too long. They should only cover as much as one sixth of the area of the sandpit. Go to the sandpit to find out how much one sixth is and then come back to change them.*
>
> [pause] *If you need to hear what I said again, point at me and click on the big middle button.*

Finally, the red bird represents the swings, which need to be increased. The rule asks the user to compare two fractions and select the one that represents the larger amount. This exercise, as confirmed by the studies, was expected to be the most difficult one for the users.

> *Hi, I am the red bird. The swings are not big enough and we want to give them as much area as possible. We can make them bigger by one third of their current area or bigger by one fourth, whichever covers more ground. You have to decide!*
>
> [pause] *If you need to hear what I said again, point at me and click on the big middle button.*

B.3 Software implementation

The Virtual Playground was developed for a CAVE-like immersive projection-based display, using VRCO's CAVELib platform[2] and OpenGL Performer[3] as the graphics application program interface

[2] More information on the CAVELib can be found at VRCO's website: http://www.vrco.com [last accessed: March 2006].
[3] http://www.sgi.com [last accessed: March 2006].

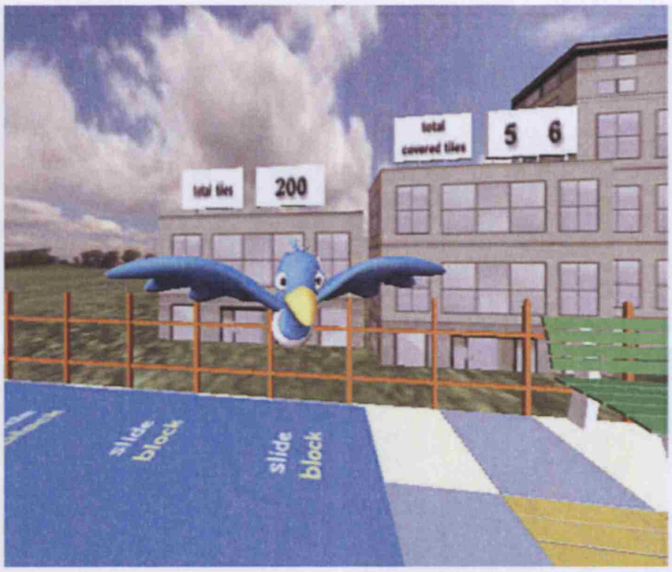


Figure B.4: The blue bird, when approached, communicates the rule for restructuring the slide area in the Virtual Playground.

(API). CAVELib provides transparent access to the virtual reality hardware, taking care of trackers and input devices, and handling the details of correct stereoscopic rendering for whatever display device is being used -whether it is a CAVE, a curved screen display, a single wall display or a desktop screen (Figure B.5).

OpenGL Performer is a scene graph based API which allows to hierarchically represent application data such as geometry, light sources, transformations, etc. The complex interaction between objects and behaviour of the Virtual Playground application was programmed using the XP (eXtended Performer) scripting language (Pape et al., 1998), the basic structure of which had to be extended with the addition of classes for the playground's "intelligent" ground, the behaviour of the blocks, the different views, the timers, and the handling of the sound. These classes were written in C++ and OpenGL Performer. As XP essentially rests on top of the basic CAVELib and OpenGL Performer layers, an XP scene graph is built of nodes which consist of an OpenGL Performer node plus behaviour. This set of tools was chosen for implementation due to the researcher's familiarity and long experience with their use.

The 3D models of the environment were created by a professional modeller and animator who was asked to create a believable (but not necessarily photorealistic) and colourful playground. Basic research was carried out concerning the play equipment that would be included in this digital playground, trying to include at least the objects that were most popular with children. Hence the list of six was formed (roundabout, slide, crawl tunnel, monkey bars, and swings) and the objects were modelled after real playgrounds from sketches and photos (Figure 5.4) using Maya. The models were then optimised in order to keep the polygon count as low as possible and ensure real-time frame rates. The most complex model was the tree, counting 19000 triangles, followed by the owl with 8000 and each bird with 6000 triangles (Figure B.6). In some cases where animation was required, multiple models were created for

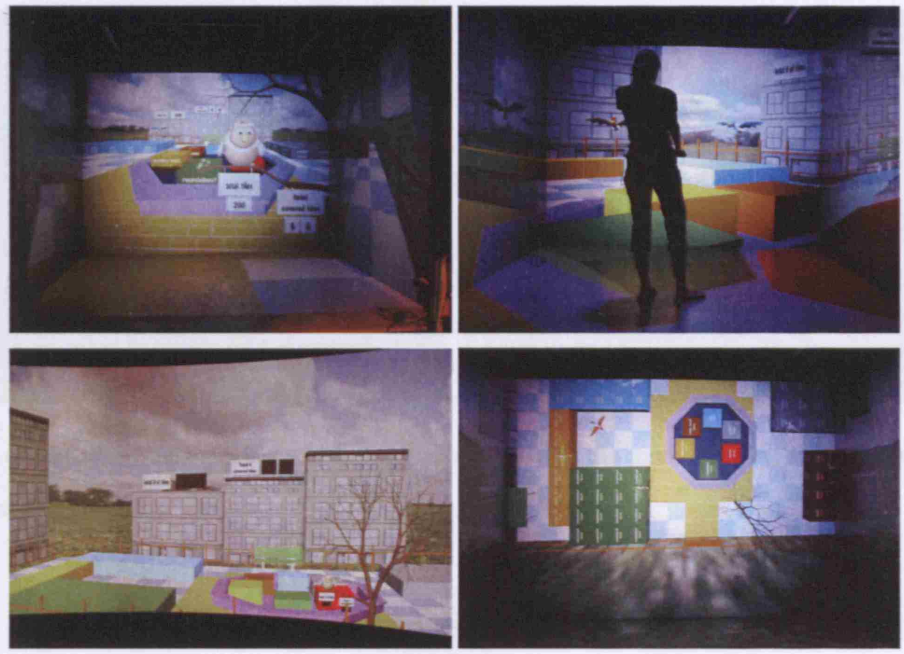


Figure B.5: Views of the Virtual Playground environment as displayed in different immersive projection-based systems, such as the ReaCTor^{TM} (above row and lower right), and a curved-screen Reality Theatre (lower left).

a single object (the owl, for example, was comprised of 37 different models that were "flipped" in a looped sequence when the owl was talking, in order for the eyelids and mouth to create the perception of movement). The models were carefully created so no synchronisation of the lips with the audio narrative would be required. On the contrary, the movement of the swings, the roundabout and other elements that "came to life" after the tasks were completed, did not require extra models, as graphical transformations were applied to the scene graph programmatically. The water fountain that filled the pool when all the cubes were gone was programmed using a particle system.

All textures were created by the researcher using drawings and images from texture libraries that were edited with Adobe Photoshop CS®. The sounds were recorded professionally with three different voices (the owl in an un-echoic room at the University of New York Buffalo), and edited by the researcher using Adobe's Audition®. For some of the birds, where sounds had to be changed or re-recorded later when the professional studio was not available anymore, AT&T's online free text-to-speech tool was used[4], resulting in some funky sounding bird voices, which, however, gave a more playful tone to the environment.

The programming of the narrative and the environment included a total of 24 "scenes" written in the XP scripting language (Figure B.7), which display and control the behaviour of 159 models and 48 sound files. Each scene is essentially a text file, which can be easily changed and adjusted without requiring a re-compilation of the code (the scene files are listed in Figure B.8).

[4]AT&T Natural Voice, http://www.research.att.com/projects/tts/demo.html [last accessed: March 2006].

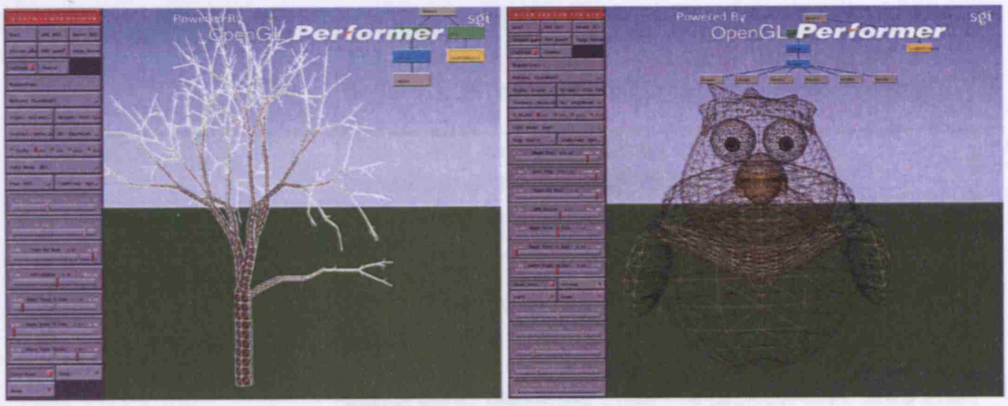


Figure B.6: The wireframe models and scene graphs of two of the more complex objects designed for the Virtual Playground.

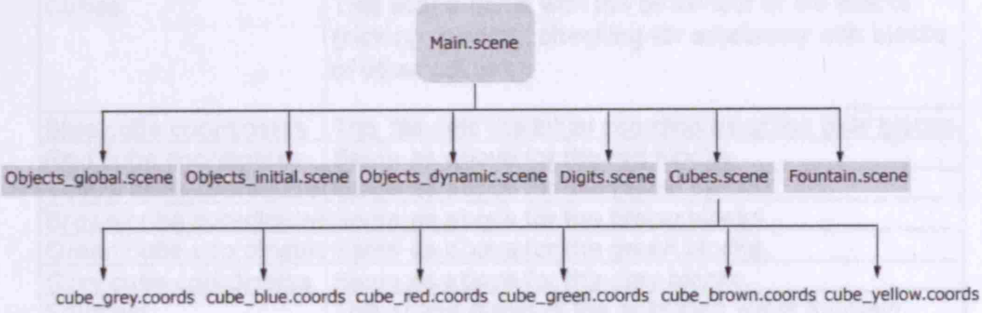


Figure B.7: The scene file structure of the Virtual Playground implementation.

An example of one of these scene files, the Main scene, is listed below.

```
# ==========================
# Virtual Playground
# Maria Roussou,2004
# Main.scene
# ==========================

light(position = "1 1 1", ambient="0 0 0", diffuse = "1 1 1",)
light(position = "-1 -1 1", ambient="0 0 0", diffuse = "1 1 1")
light(position = "0 1 0", ambient="0 0 0", diffuse = "1 1 1")

sobject (file=Skydome.pfb, scale=300, translate="0 0 -0.1",
rotate="90 0 0") sobject (file=Grass.pfb, scale=300, translate="0
0 0.3", rotate="90 0 0")
```

Scene files	Purpose
Main	The main scene is executed when the program begins. It is responsible for calling all other scenes.
Objects_global	This scene loads and deals with the behaviour of all the models that create the playground surroundings as well as the owl and birds.
Objects_initial	This scene is responsible for displaying the initial distorted playground elements when the playground is first loaded.
Objects_dynamic	This scene is responsible for displaying the correct playground elements once the task on their area has been completed successfully.
Digits	This scene deals with the behaviour of the counters that are used to count the total blocks on the playground.
Cubes	This scene deals with the behaviour of the blocks (picking, placing, checking for adjacency with blocks of other colours).
Blue cube coordinates	This file sets the initial coordinates of the blue blocks.
Red cube coordinates	Same as above for the red blocks.
Yellow cube coordinates	Same as above for the yellow blocks.
Brown cube coordinates	Same as above for the brown blocks.
Green cube coordinates	Same as above for the green blocks.
Grey cube coordinates	Same as above for the grey blocks.
Fountain	This scene displays the animated water fountain. It is switched on by the Main scene when all the problem tasks have been completed.

Figure B.8: A list of the most important scene files used for the creation of the Virtual Playground.

```
# --- Keyframe for top-down view
keyframe (file=smallkeypath2,loop=0,
initstate=off, name=small_keyframe2)
{
    keyframe (file=smallkeypath, loop=0, initstate=off,
    name=small_keyframe)
    {
        scene(file=Objects_global.scene)
        switch (name=objsinitial, initval=on)
        {
            transform(scale=1)
            {
```

```
            scene(file=Objects_initial.scene)
        }
    }
    switch (name=objsfinal, initval=off)
    {
        transform (scale=1)
        {
            scene(file=Objects_dynamic.scene)
            scene(file=Digits.scene)
        }
    }
    switch(name=cubeswitch, initval=off,
        eventMessage = "switchon, pick_sound, play",
        eventMessage = "switchon, pick_sound, stop, 2",
        eventMessage = "switchoff, drop_sound, play",
        eventMessage = "switchoff, drop_sound, stop, 2")
    {
        scene (file=Cubes.scene)
        object(file=beam.pfb, attach=on)
    }

vpplane(xdim=20, ydim=10, digitnode=digit_nrselect,
name=vpplane1,
        cubeswitch1=yellow_switch,
        thingswitch1=yellowthing_switch,
        thingtrans1=yellowthing_translator,
        cubeswitch2=orange_switch,
        thingswitch2=orangething_switch,
        thingtrans2=orangething_translator,
        cubeswitch3=blue_switch,
        thingswitch3=bluething_switch,
        thingtrans3=bluething_translator,
        cubeswitch4=grey_switch,
        thingswitch4=greything_switch,
        thingtrans4=greything_translator,
```

```
    cubeswitch5=red_switch,
    thingswitch5=redthing_switch,
    thingtrans5=redthing_translator,
    cubeswitch6=green_switch,
    thingswitch6=greenthing_switch,
    thingtrans6=greenthing_translator,

#forbidden1 is footpath
eventMessage = "forbidden1, forbidden_on_footpath_sound, play",
eventMessage = "forbidden1, forbidden_on_footpath_sound, stop, 2",

#forbidden2 is park bench
eventmessage = "forbidden2, forbidden_onbench_sound, play",
eventmessage = "forbidden2, forbidden_onbench_sound, stop, 2",

#forbidden3 is fence
eventmessage = "forbidden3, forbidden_next2fence_sound, play",
eventmessage = "forbidden3, forbidden_next2fence_sound, stop, 2",

#tile is occupied
#eventmessage = "occupied, %world, sky 1 1 0",
eventmessage = "occupied, forbidden_adjacent_block_sound, play",
eventmessage = "occupied, forbidden_adjacent_block_sound, stop, 2",

#adjacent to tile of different colour
eventmessage = "adjacent, forbidden_adjacent_block_sound, play",
eventmessage = "adjacent, forbidden_adjacent_block_sound, stop, 2",

#everything is done!
eventmessage = "finished, kids_clapping_snd, play",
eventmessage = "finished, kids_clapping_snd, stop, 6",
eventmessage = "finished, roundabout_spinner, start",
eventmessage = "finished, static_swing_switch, off",
eventmessage = "finished, moving_swing_switch, on",
eventmessage = "finished, move_left_swing, swing",
```

```
        eventmessage = "finished, move_middle_swing, swing",
        eventmessage = "finished, move_right_swing, swing",
        eventmessage = "finished, fountain_switch, on",
        eventmessage = "finished, fountain_snd, play, 1")
    } #end keyframe for plane view
} #end keyframe

# --- Switch to start water fountain
        switch (name=fountain_switch, initval=off)
        {
            scene(file=Fountain.scene)
        }

# --- Keyframe for initial entrance into path
keyframe(file=path_initial.path, duration=10, name=initialpath)

# --- Keyframe for tour of playground path
keyframe(file=path_tour.path, duration=35, name=tourpath)

# --- Triggers to setup world wandtrigger (sphere ="0 0 0 2000",
initstate=on,
    eventmessage = "enter, %world, clip 0.1 2000",
    eventMessage = "enter, ambient_bird_sound, play",
    eventmessage = "enter, %navigator, position 0.125 12.236 -0.100 180",
    eventmessage = "enter, initialpath, start",
    eventmessage = "enter, %navigator, attach initialpath",
    eventmessage = "enter, %navigator, release, 10",
    eventMessage = "enter, %navigator, speed 0, 10.5",
# - reach owl and start narrative
    eventMessage = "enter, owl_not_talking_switch, off, 10.3",
    eventMessage = "enter, owl_01_welcome_sound, play, 10.5",
# - tour user around playground while owl is talking
    eventmessage = "enter, tourpath, start, 11",
    eventmessage = "enter, %navigator, attach tourpath, 11",
    eventmessage = "enter, %navigator, release, 42",
```

```
    eventMessage = "enter, %navigator, speed 0, 42.5",
# - return to owl again
    eventmessage = "enter, owl_talking, stop, 31.2",
    eventmessage = "enter, owl_not_talking_switch, on, 31.2",
    eventmessage = "enter, owl_not_talking_switch, off, 31.8",
    eventmessage = "enter, owl_talking, start, 31.8",
    eventMessage = "enter, owl_02_sound, play, 31.8",
    eventmessage = "enter, owl_talking, stop, 43",
    eventmessage = "enter, owl_not_talking_switch, on, 43",
    eventmessage = "enter, owl_not_talking_switch, off, 43.8",
    eventmessage = "enter, owl_talking, start, 43.8",
    eventMessage = "enter, owl_03_sound, play, 43.8",
    eventmessage = "enter, owl_talking, stop, 56.31",
    eventmessage = "enter, owl_not_talking_switch, on, 56.31",
    eventMessage = "enter, initialtrigger, enable, 56")

# - wait for red button1, then switch to construction mode
wandtrigger (sphere ="0 0 0 1000", name=toggleview_trigger,
    eventmessage = "button1, vpplane1, toggleView")

wandtrigger (sphere ="0 0 0 1000", name=initialtrigger,
initstate=off,
    eventmessage = "button1, initialtrigger, disable",
    eventmessage = "button1, objsfinal, toggle",
    eventmessage = "button1, objsinitial, toggle",
    eventmessage = "button1, cubeswitch, toggle",
    eventMessage = "button1, owl_04_sound, play, 0.5",
    eventmessage = "button1, owl_talking, start, 0.5",
    eventmessage = "button1, owl_not_talking_switch, off, 0.5",
    eventMessage = "button1, owl_06_sound, play, 31",
    eventmessage = "button1, owl_not_talking_switch, on, 42",
    eventmessage = "button1, initialbirdviewtrigger, enable, 40.5")

# - wait for blue button3, then switch to topview wandtrigger
(sphere ="0 0 0 1000", name=initialbirdviewtrigger, initstate=off,
```

```
    eventmessage = "button3, initialbirdviewtrigger, disable",
    eventmessage = "button3, initialbirdview2trigger, enable")

wandtrigger (sphere ="0 0 0 1000", name=initialbirdview2trigger,
initstate=off,
    eventmessage = "button3, initialbirdview2trigger, disable",
    eventmessage = "button3, owl_not_talking_switch, off, 1.16",
    eventMessage = "button3, owl_07_sound, play, 1.16",
    eventMessage = "button3, owl_05a_sound, play, 29.6",
    eventMessage = "button3, owl_05b_sound, play, 45.7",
    eventMessage = "button3, owl_08_sound, play, 63.1",
    eventMessage = "button3, owl_09_sound, play, 79.2",
    eventMessage = "button3, %navigator, speed 1.5, 94.7",
    eventMessage = "button3, owl_11_sound, play, 92.7",
    eventmessage = "button3, owl_not_talking_switch, on, 95.1",
    eventmessage = "button3, owl_talking, stop, 95.1")

# --- Triggers for getting to plane view and back wandtrigger
(sphere ="0 0 0 1000", initstate=on, name=view1_trigger,
    eventmessage = "button3, go_high_sound, play",
    eventmessage = "button3, go_high_sound, stop, 2",
        eventmessage = "button3, small_keyframe, on",
        eventmessage = "button3, small_keyframe2, on",
        eventmessage = "button3, small_keyframe, start, 0.1",
        eventmessage = "button3, small_keyframe2, start, 0.1",
    eventmessage = "button3, small_keyframe2, gotouser 1, 0.5",
        eventmessage = "button3, view1_trigger, disable, 2",
        eventmessage = "button3, view2_trigger, enable, 2",
        eventmessage = "button3, %navigator, fly on",
        eventmessage = "button3, %navigator, speed 0",
        eventmessage = "button3, toggleview_trigger, disable")

wandtrigger (sphere ="0 0 0 1000", initstate=off,
name=view2_trigger,
    eventmessage = "button3, go_ground_sound, play",
```

```
    eventmessage = "button3, go_ground_sound, stop, 2",
        eventmessage = "button3, small_keyframe, off",
        eventmessage = "button3, small_keyframe2, off",
        eventmessage = "button3, small_keyframe, reset",
        eventmessage = "button3, small_keyframe2, reset",
        eventmessage = "button3, view1_trigger, enable, 2",
        eventmessage = "button3, view2_trigger, disable, 2",
        eventmessage = "button3, %navigator, fly off",
        eventmessage = "button3, %navigator, speed 1.5",
        eventmessage = "button3, toggleview_trigger, enable")

# --- Trigger for resetting position in front of owl wandtrigger
(sphere ="0 0 0 1000", initstate=on, name=reset_position_trigger,
    eventmessage = "button4, %navigator, position -0.735 4.011 -0.1 180")

# --- Box where cubes get added to pool again # -   box = lowleftX
lowleftdepth lowleftheight uprightX uprightdepth uprightheight
#exact box around pool: wandtrigger (box ="-3.0 -3 0 2.2 2 10",
#larger box around pool: wandtrigger (box ="-4.0 -3 0 3 3 10",

wandtrigger (box ="-3.0 -3 0 2.2 2 10",
    eventmessage = "button2, drop_sound, play",
    eventmessage = "button2, drop_sound, stop, 2",
    eventmessage = "button2, yellow_multiswitch, disableactive",
    eventmessage = "button2, orange_multiswitch, disableactive",
    eventmessage = "button2, blue_multiswitch, disableactive",
    eventmessage = "button2, grey_multiswitch, disableactive",
    eventmessage = "button2, red_multiswitch, disableactive",
    eventmessage = "button2, green_multiswitch, disableactive")

# --- Define sounds sound(name=ambient_bird_sound, duration=23.06,
loop=1, file="ambient_birds.wav") sound(name=pick_sound,
duration=0.201, file="fdbck_pick_block.wav", maxdistance=-1,
amplitude=0.5) sound(name=drop_sound, duration=0.069,
file="fdbck_drop_block.wav", maxdistance=-1, amplitude=0.5)
```

```
sound(name=go_high_sound, duration=1.743,
file="fdbck_go_high.wav", maxdistance=-1, amplitude=0.5)
sound(name=go_ground_sound, duration=1.164,
file="fdbck_go_ground.wav", maxdistance=-1, amplitude=0.5)

sound(name=forbidden_adjacent_block_sound, duration=2.765,
file="fdbck_forbidden_adjacent_block.wav")
sound(name=forbidden_onbench_sound, duration=2.765,
file="fdbck_forbidden_on_bench.wav")
sound(name=forbidden_next2fence_sound, duration=2.765,
file="fdbck_forbidden_next2fence.wav")
sound(name=forbidden_on_footpath_sound, duration=2.765,
file="fdbck_forbidden_on_path.wav") sound(name=kids_clapping_snd,
duration=5.576, file="fdbck_kids_clapping.wav")

sound(name=fountain_snd, duration=4.2, loop=1,
file="fountain_loop3.wav")

sound(name=owl_01_welcome_sound, duration=21.068,
file="owl_01_welcome.wav") sound(name=owl_02_sound,
duration=11.946, file="owl_02_unfortunately.wav")
sound(name=owl_03_sound, duration=12.517,
file="owl_03_soherewego.wav") sound(name=owl_04_sound,
duration=29.824, file="owl_04_woo.wav") sound(name=owl_05a_sound,
duration=15.633, file="owl_05_doyousee.wav")
sound(name=owl_05b_sound, duration=16.874,
file="owl_05_youcanpoint.wav") sound(name=owl_06_sound,
duration=10.689, file="owl_06_whenyouare.wav")
sound(name=owl_07_sound, duration=28.18,
file="owl_07_tochange.wav") sound(name=owl_08_sound,
duration=15.798, file="owl_08_youcanmake.wav")
sound(name=owl_09_sound, duration=13.025,
file="owl_09_thesesigns.wav") sound(name=owl_10_sound,
duration=4.932, file="owl_10_whenyouarefinished.wav")
sound(name=owl_11_sound, duration=2.765,
```

```
file="owl_11_readygetsetgo.wav")


# ============== end of file
```

The fact that CAVELib and OpenGL Performer now also run on the Linux and Windows operating systems means that the development of the VE was not dependent on the availability of a SGI computer, but could take place on different platforms, including a laptop computer, using the CAVE simulator.

B.4 Recording and playing back activity

The programme had to be slightly altered for the passive VR condition. In this case, the interactive features had to be disabled from the user's input devices, yet all output, such as the feedback messages, had to be preserved. When played back, the interaction had to seem as if performed between the system and an avatar or robot (Figure B.9).

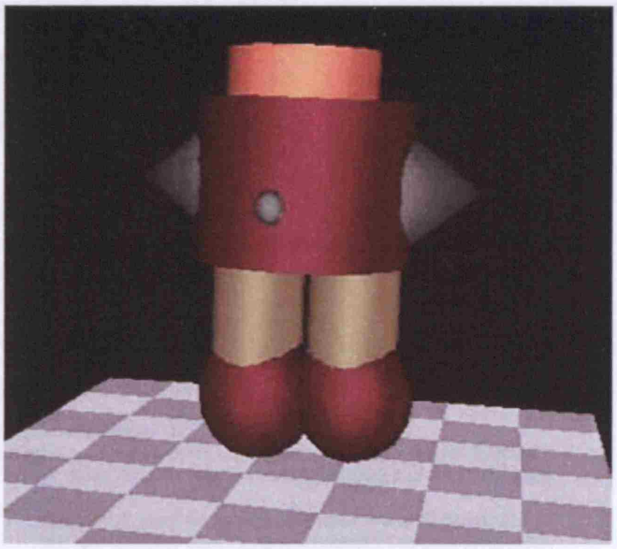


Figure B.9: The model of the robot "avatar", used to perform activity within the Virtual Playground of the passive VR condition.

The programming required to implement this feature essentially extended the main code, written for the interactive VR condition, with a recording feature to capture user input and play it back later. Several interactive session performed by the researcher were recorded, meaning that every event triggered during the experience was written in a file. Then the program was executed reading the file of events that was selected and "attaching" the events to the robot.

Pseudocode describing the technical implementation of this can be seen in Figure B.10, in the communication between the researcher and one of the programmers responding to the researcher's request for help in coding.

Subject: **RE: question re. recording VR activity**
From: Alex Hill <ahill@evl.uic.edu>
Date: 4/28/2005 6:34 PM
To: Maria Roussou <m.roussou@cs.ucl.ac.uk>

Well, back in the hey-day I'm sure we could find an eager beaver.
Unfortunately, it seems the students are now spoiled by YG and could'nt program their way out of a wet paper bag.
The major upgrade to the current version of YG is that you can access ALL of the variables (i.e. file,position,floor,etc.) in an event.
So, you could set up a CAVETracker node as follows:

```
CAVETracker myTracker(when(its_time,myWriteFile.values($position0 $position1 $position2 $orientation0 $orientation1 $orientation2),
                              myWriteFile.write))
   {
   object(file(wand.pfb))
   }
```

So if you send myTracker and event called "its_time" once a second.

```
timer(integer,
       endValue(100),
       when(changed,myTracker.event(its_time)))
```

Then he will populate the values in myWriteFile and force him to add them to the file a hundred times.

```
writeFile myWriteFile(file(store_tracker_position.dat))
```

Then, later, you could use a pathMover node to read the data file and move a transform smoothly between each value:

```
timer dummyTimer(duration(100),
                 when(changed,myDummyTracker.set($value))

pathMover myDummyTracker(file(store_tracker_position.dat))
  {
   object(file(wand.pfb))
   }
```

Alternatively, youd can read those values back in with a readFile node:

```
timer(integer,
     endValue(100),
     when(changed,myReadFile.event(read_value)))
```

populate a mover node with appropriate start values and end values:

```
readFile myReadFile(file(store_tracker_position.dat),
                  when(read_value,myDummyTracker.startPosition($values0 $values1 $values2),
                              myDummyTracker.startOrientation($values3 $values4 $values5),
                              read,
                              myDummyTracker.endPosition($values0 $values1 $values2),
                              myDummyTracker.endOrientation($values3 $values4 $values5),
                              myDummyTimer.start))
```

and, start moving between the two:

```
timer myDummyTimer(duration(100),
                   when(changed,myDummyTracker.set($value)))
mover myDummyTracker()
   {
   object(file(wand.pfb))
   }
```

I'm sure we could also figure out a way to store button pushes and navigation in a file.
Between the tracker data, button pushes, and navigation you can reproduce the behavior of an avatar.
alex

Figure B.10: Pseudocode for recording and playing back activity in the Virtual Playground.

B.5 Constructing the LEGO playground

Different shapes and sizes of LEGO bricks were collected in order to create a playground that was as close as possible to the virtual playground layout (Figure B.11).

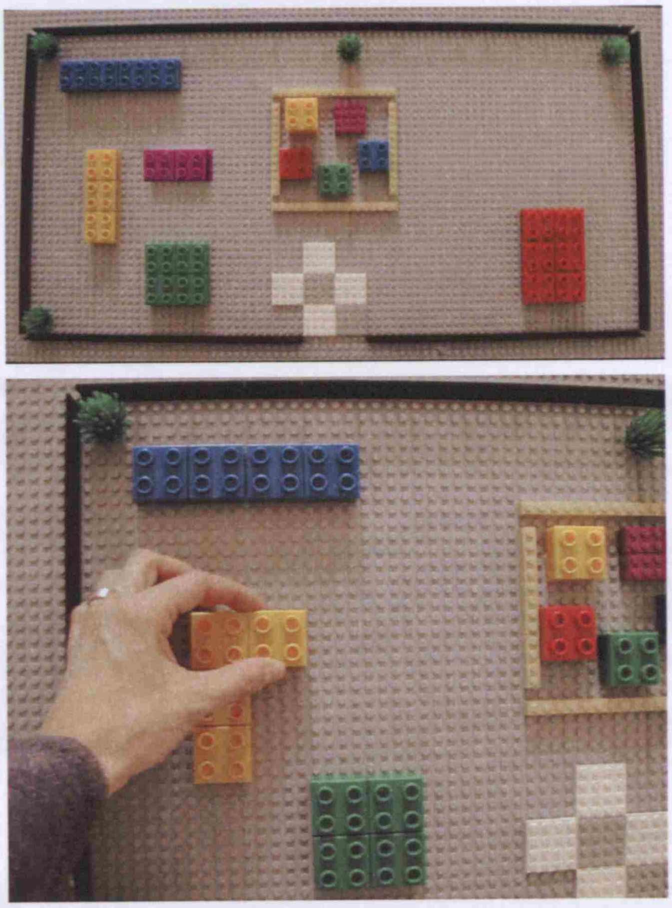


Figure B.11: Different shapes and sizes of LEGO bricks were collected in order to create a playground that was as close as possible to the virtual playground layout.

Finding bricks of different shapes and colours to meet this purpose of mapping as accurately as possible the footprint of the virtual playground was unexpectedly difficult. The process of collecting the bricks used to construct the playground model included visiting toy stores and specialty shops in three different countries, as well as purchasing individual bricks from on-line collectors through auction web sites (Figure B.12).

The rule for each area was printed onto laminated coloured cardboard, on a different card per area. Each card was placed on the LEGO playground, directly onto the bricks of the area that it referred to. On one side it had an image of a bird while on the other side it included the rule related to the bird and the area of the same colour. The rule was written with the exact same wording used for the oral rules that were spoken out by the virtual birds in the Virtual Playground (Figure B.13).

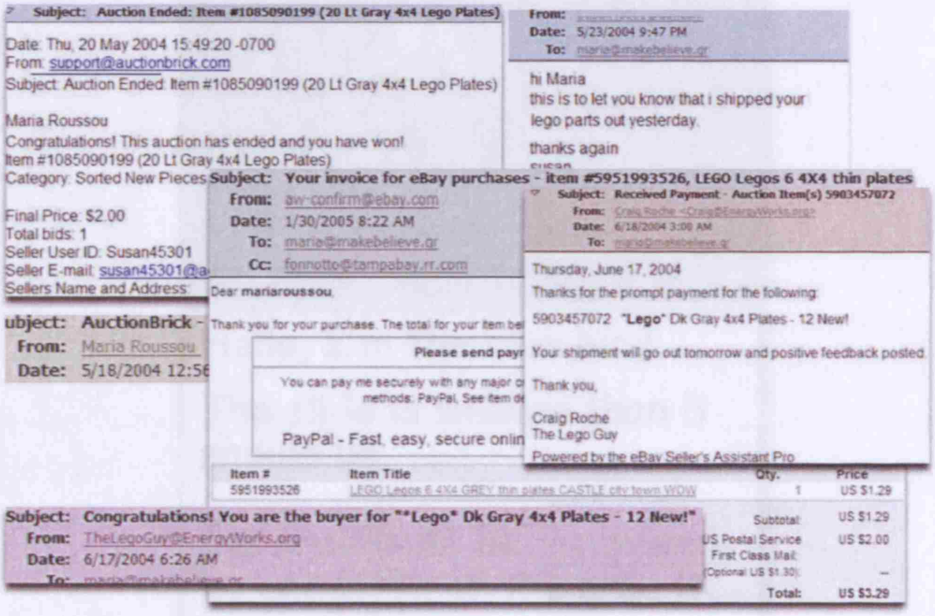


Figure B.12: The LEGO bricks used to construct the playground model were purchased from 10 different sources, many on-line through collectors via ebay and Auction Brick.

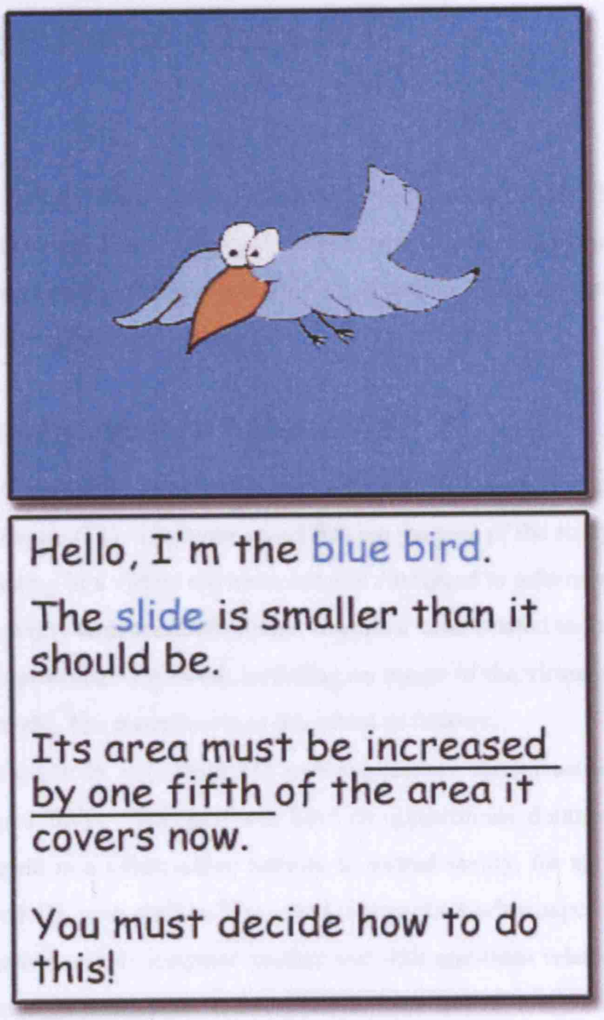


Figure B.13: A sample of the rule card used to communicate the rule for the swings area of the LEGO playground.

Appendix C

Main Experiment Material

This appendix contains further information concerning the experimental study. Specifically, information is included about the letter and consent form given to the parents, the questionnaires given to the children prior to and after the experience, the various methods and material used to recruit participants, and the gift pack given to each participant in the study.

C.1 Parent information and consent form

An invitation in the form of a cover letter was prepared for distribution to parents, informing them of the study and its purpose (Figure C.1). The letter noted that the purpose of the study was to determine what children learn by interacting in a virtual environment and continued to inform parents that we would be observing their child's ability to accomplish simple cognitive tasks related to mathematical fractions. A short description of the procedure followed, including an image of the virtual reality environment that would be used for the study. The procedure was described as follows:

"In the first part of the study, your child will answer questions about fractions, such as the questions asked in the Key Stage 2 SATs. This part will have an approximate duration of 20 minutes. Next, your child will participate in a construction activity in virtual reality, for approximately 30 minutes. After completing the activity, your child will be asked to describe his/her experience in a short interview (approximately 10 minutes) and to complete another test with questions related to fractions, similar to the first one (approximately 20 minutes). A description of the activity and a consent form are included below. Your child will be videotaped during the activity and the interview, for later observation by the researchers. The video and questionnaires will be used for data analysis purposes only and will be kept entirely confidential. If your child is known to have suffered from epilepsy, we regret that we are unable to accept his/her participation in the virtual reality part of the study. However, your child can still participate in the other parts of the study. The consent form included at the end of this document, authorises the information your child provides to be used for research purposes only. We would appreciate it if you would complete and return the form at your earliest convenience. Please feel free to contact us with any questions or comments you may have about the project."

The consent form, which was designed according to the general guidelines provided by the UCL Ethics committee on Human subject research, is shown in Figure C.4.

University College London
Gower Street
London WC1E 6BT UK

Department of Computer Science

Invitation
to participate in a Virtual Reality research study

Dear Parent,

We are conducting a study observing how and what children learn in a virtual reality environment and we would like to invite your child to participate.

The purpose of this study is to determine what children learn by interacting in a virtual environment. We will be observing their ability to accomplish simple cognitive tasks related to mathematical 'fractions'. In the first part of the study, your child will answer questions about fractions, such as the questions asked in the Key Stage 2 SAT's. This part will have an approximate duration of 20 minutes. Next, your child will participate in a construction activity in virtual reality, for approximately 30 minutes. After completing the activity, your child will be asked to describe his/her experience in a short interview (approximately 10 minutes) and to complete another test with questions related to fractions, similar to the first one (approximately 20 minutes). A description of the activity and a consent form are included below.

Your child will be videotaped during the activity and the interview, for later observation by the researchers. The video and questionnaires will be used for data analysis purposes only and will be kept entirely confidential. If your child is known to have suffered from epilepsy, we regret that we are unable to accept his/her participation in the virtual reality part of the study. However, your child can still participate in the other parts of the study.

The consent form included at the end of this document, authorizes the information your child provides to be used for research purposes only. We would appreciate it if you would *complete and return the form* at your earliest convenience. Please feel free to contact us with any questions or comments you may have about the project.

Sincerely,

Maria Roussou

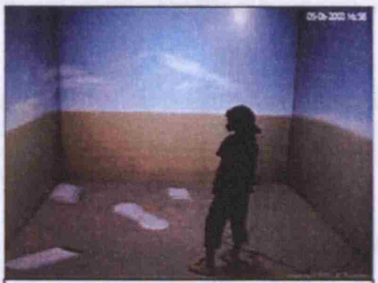
Vision Imaging and Virtual Environments
Department of Computer Science
University College London
Gower Street, London WC1E 6BT

Figure C.1: The cover letter given to parents along with a detailed information sheet and an informed consent form.

Introduction
Your child is being invited to take part in a research study, which aims to evaluate how children interact and learn in a virtual environment. Before you and your child decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Feel free to ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you would like your child to take part.

Procedures
This study broadly looks at aspects of the use of digital environments for learning and education, specifically how the ability to interact in a virtual environment may help learning. It is important that the whole testing procedure is a positive experience. Firstly the entire process will be explained to your child and an opportunity will be given for him/her or you/accompanying caregiver to ask any questions.

Overall the procedures of the study are as follows:
- You will be asked to sign the consent form that comes with this document.
- In the first part of the study, your child will be asked to fill out a questionnaire with math questions similar to those asked in the Key Stage 2 SAT math test.
- Next, your child will take part in an activity in the virtual reality room. The activity will involve the design and "construction" of a space, such as a virtual playground.
- If your child takes part in the virtual reality activity, s/he will have to wear a pair of lightweight plastic glasses (which can be worn over eyeglasses if necessary) and use a handheld device with a joystick and buttons for moving virtual building blocks around. A small microphone may also be attached to your child for recording her/his voice when speaking.
- The task will be explained to your child who will have a chance to practice moving objects around in the virtual space.
- After completing the task, your child will be interviewed about his/her experience and then asked to complete another test with questions related to fractions, similar to the first one.
- The expected duration of participation in the research will be approximately 1½ hours.



An 8-year old girl while interacting in the virtual reality room during an earlier phase of this study.

This study is being conducted as part of a PhD research. The study will take place in central London, at UCL's Department of Computer Science where the immersive virtual reality room is located.

Principal Investigator
Professor Mel Slater
Tel.: 0207 6793709
e-mail: m.slater@cs.ucl.ac.uk

Project Researcher and Contact
Maria Roussou, PhD Student
Department of Computer Science,UCL
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Project Researcher
Dr. Martin Oliver
Senior Lecturer in ICT in Education
London Knowledge Lab, Inst. of Education
Tel.: 0207 763 2168
e-mail: m.oliver@ioe.ac.uk

See http://www.cs.ucl.ac.uk/staff/M.Roussou/research/ for more information and images.

UCL Virtual Reality study: information Page 2/3

APPROVED BY THE UNIVERSITY COLLEGE LONDON'S COMMITTEE ON THE ETHICS OF NON-NHS HUMAN RESEARCH, No. 0171/001

Figure C.2: The front side of the information sheet given to parents.

A note about virtual reality equipment

Risks, Discomforts and Benefits
It is not anticipated that your child will experience any discomfort from the testing procedures. The activity will resemble play with a construction kit in a computer environment and should not be physically demanding.

When using virtual reality systems, some people sometimes experience some degree of nausea. There have been various reported side effects of using virtual reality equipment, such as "flashbacks." With any type of video equipment there is a possibility that an epileptic episode may be generated. This, for example, has been reported for computer video games. For this reason we regret that *we are unable to accept volunteers who are known to have suffered from epilepsy*.

Testing will be terminated immediately upon the request of your child, yourself or any familiar adult or if your child indicates any discomfort/undue tiredness or if any abnormal responses occur. Participation in this study should be an interesting and enjoyable experience and the results obtained are expected to assist Computer Scientists and Educators in evaluating the effects and potential benefits of interactivity in a virtual learning environment.

Confidentiality
Any information that is shared during the study will be treated with strict confidence and once the study is completed, it will not be possible to identify individuals. Throughout the study only the aforementioned researchers will have access to the information. The data will be collected and stored in accordance with the Data Protection act for 5 years, after which time it will be destroyed.

Request for Further Information
You or your child are encouraged to discuss any concerns regarding the study with the Principle Investigator at any time, and to ask any questions that you might have.

Refusal or Withdrawal
You or your child may refuse to participate in the study and if you do consent to participate then you will be free to withdraw from the study **at any time** without consequence, fear or prejudice. If you or your child decides to withdraw from the study, then please contact the Principal Investigator at the earliest opportunity. In the event of withdrawal, all data pertaining to your child will be destroyed.

Comment or Concerns During the Study
If you have any comments or concerns you should discuss these with the Principal Researcher. If you wish to go further and complain about any aspect of the way you have been approached or treated during the course of the study, you should email the Chair of the UCL Committee for the Ethics of Non-NHS Human Research (gradschoolhead@ucl.ac.uk) or send a letter to: The Graduate School, North Cloisters, Wilkins Building, UCL, Gower Street, London WC1E 6BT who will take the complaint forward as necessary.

Prior to taking part in the research a copy of this information sheet is given to you to keep and an informed consent form is provided for you to sign.

Thank you for considering taking part in this study.

UCL Virtual Reality study: information Page 3/3

APPROVED BY THE UNIVERSITY COLLEGE LONDON'S COMMITTEE
ON THE ETHICS OF NON-NHS HUMAN RESEARCH. No 0171/001

Figure C.3: The back side of the information sheet given to parents.

UCL
Department of Computer Science

University College London
Gower Street
London WC1E 6BT UK
tel: 0207 679 3664
fax: 0207 387 1397
m.roussou@cs.ucl.ac.uk

Informed Consent Form

for participation in a Virtual Reality study

Please read and answer the following questions carefully:

Have you read the information sheet about this study?	YES/NO
Have you had an opportunity to ask questions about the procedure?	YES/NO
Have you received satisfactory answers to all your questions?	YES/NO
Have you received enough information about this study?	YES/NO
Do you understand that your child is free to withdraw from this study at any time and without giving a reason for withdrawing?	YES/NO
Do you understand and accept the risks associated with the use of virtual reality equipment?	YES/NO
Do you agree that your child takes part in this study?	YES/NO

We would like to videotape your child when in the virtual environment. These tapes will be used for data analysis purposes only and will be kept entirely confidential.

Do you agree that your child is videotaped?	YES/NO
Do you agree that your child is audiotaped?	YES/NO

Please check:

- I certify that my child does not have epilepsy ☐
- I take responsibility that my child will not be engaging in any kind of complex activity, such as riding a bicycle or roller-blading, within 3 hours after the termination of the study ☐

Signature(s) Parent/Guardian .... Date: ....

Name(s) in block letters...

Name of child in block letters .... Age of child: ....

Name of school: .... Year in school: ....

You are voluntarily making a decision on whether or not to consent to your child's participation in this research study. Your signature certifies that you have decided to consent for your child to participate, having read and understood the information presented. Your signature also certifies that you have had an adequate opportunity to discuss this study with the investigator and to ask questions. Your signature certifies that you give your permission for any results from this study to be used in any report or research paper, or verbal presentation, on the understanding that confidentiality will be preserved. You may retain a copy of this consent form for your records.

APPROVED BY THE UNIVERSITY COLLEGE LONDON'S COMMITTEE ON THE ETHICS OF NON-NHS HUMAN RESEARCH, No. 0171/001

Figure C.4: An Informed Consent form was given to the parent to sign prior to the child's participation in the virtual reality experiment.

A simplified version of the consent form (excluding the questions concerning the virtual reality equipment) was given to the parents of the children that took part in the non-VR group.

C.2 User demographics and profiling questionnaire

As a first step of the study, a simple questionnaire was given to each participant with the purpose of collecting basic demographic information and determining the level of prior experience with computers and virtual reality (Figure C.5).

C.3 Pre-test questionnaire

A questionnaire was designed to test the student's ability to solve basic fractions problems before entering the study. The questionnaire was given to each student to complete directly after the profiling questionnaire and prior to participating in the main experimental activity. It consisted of 2 pages with a total of 9 questions about fractions. The questions were based on SAT Key Stage 2 questions and were adjusted to this study with the help of mathematics educators (Figures C.6 and C.7). Specifically, the pre-test included questions that used the symbolic notation of fractions (questions A1, A2, A4, A5, and A8), questions to compare fractions (A5a and A5b), a question describing a real-world scenario (A2), questions with the representation of an area (A1, A6, A7, A8), and a question with a 2D pie (A9).

C.4 Semi-structured interview guide

Semi-structured interviews were carried out with all participants after the main experience. A set of research questions was specified in advance in outline form in order to make the process of data collection more systematic for each respondent. This outline used for the main study is included below.

Satisfaction Questions :

Did you enjoy the experience?

What did you like the most?

What did you dislike? Was there something you did not like?

Usability Questions :

Did you find it difficult or easy?

What was the most difficult thing for you?

Opinion / Belief Questions :

If you were to start over, what would you do differently?

If you were the designer of the (virtual or LEGO) playground, what would you add to make it more fun / to make it better?

Questions to identify if they make the connection with mathematics:

Do you think that this playground can help someone learn maths?

How do you think that this playground could help someone to learn fractions?

Questions about conceptual conflicts and learning tasks :

So what happened with the roundabout / monkey bars / slide / swings / crawl tunnel?

Would you solve it differently now that you know the answer?

Pre-test condition: ctrl | iVR | pVR

Tell us about you...	1	2	3	4
B1. What is your name?				
B2. Are you a boy or a girl? ☐ Boy ☐ Girl			(fill in the dot above the correct answer)	
B3. How old are you?				
B4. Which school do you go to? .... What year are you in school?				
B5. Do you use a computer at home?	☐ no	☐ sometimes	☐ yes	☐ yes, every day
B6. How much do you play with computer games?	☐ never	☐ sometimes	☐ every week	☐ every day
B7. Which is your favorite computer game?				
B8. Do you know what virtual reality is?			☐ No	☐ Yes
B9. Where have you seen virtual reality before?				

THANK YOU!

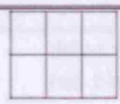
Figure C.5: The user profiling questionnaire given to each participant before the pre-test.

Pre-test condition: ctrl | lVR | pVR

Name:________________
Age :________________

The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can!

A1. Colour in $\frac{1}{2}$ of this grid:



A2. Jack's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{6}$ of the cake to Jack and keep the rest for himself.

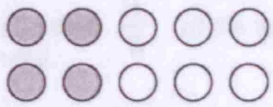
How many pieces of cake will he give to Jack? ______

Draw a picture below to show the how many pieces are for Jack and how many for Jack's father:

A3.

How many circles do you see? ______

How many circles are shaded (grey)? _____



What fraction of the total is shaded?

____

A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw them in the box

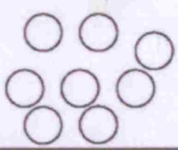
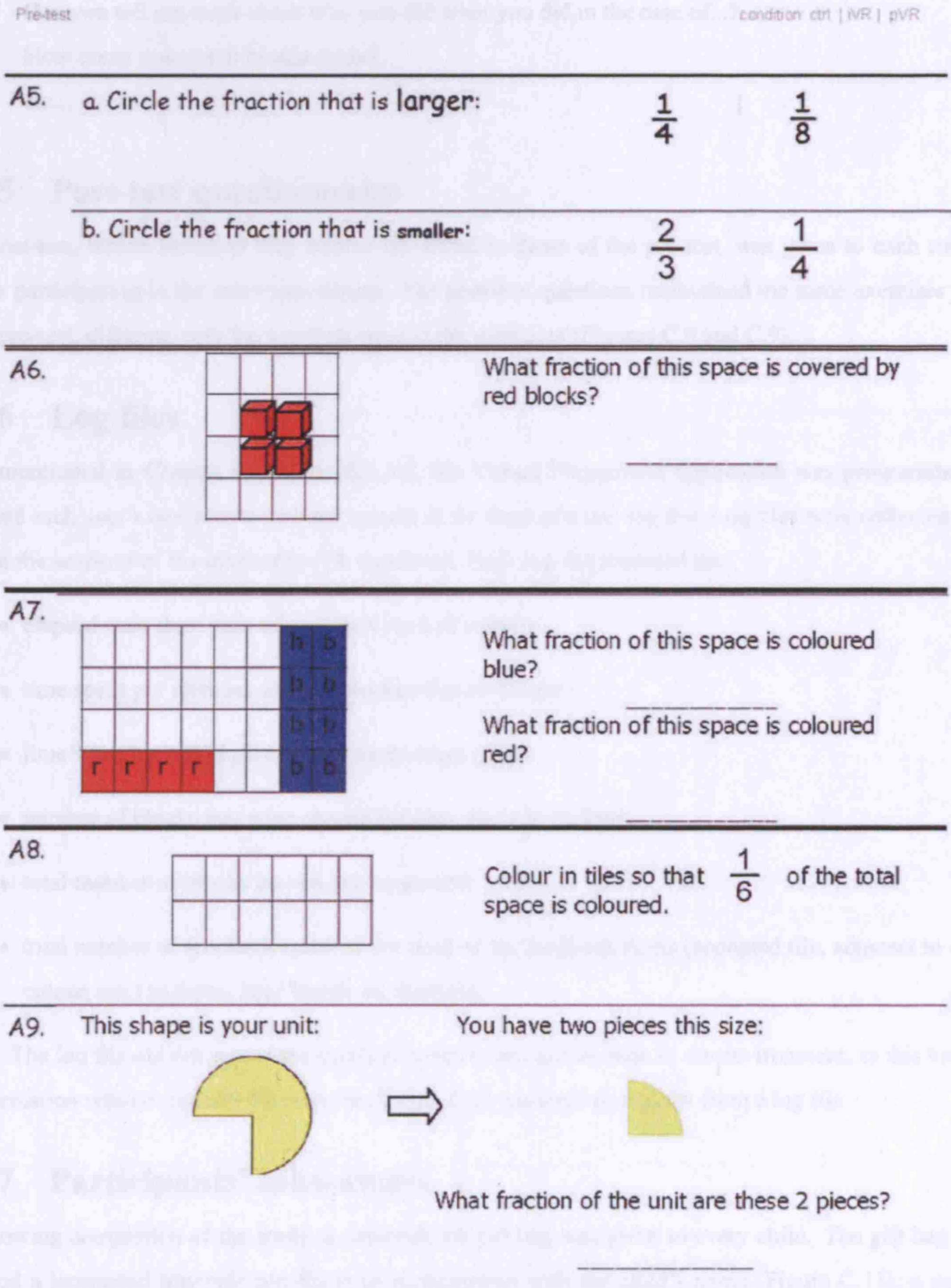


Figure C.6: The first page of the pre-test.



Pre-test condition ctrl | iVR | pVR

A5. a. Circle the fraction that is larger: $\frac{1}{4}$ $\frac{1}{8}$

b. Circle the fraction that is smaller: $\frac{2}{3}$ $\frac{1}{4}$

A6. What fraction of this space is covered by red blocks?

A7. What fraction of this space is coloured blue?

What fraction of this space is coloured red?

A8. Colour in tiles so that $\frac{1}{6}$ of the total space is coloured.

A9. This shape is your unit: You have two pieces this size:

What fraction of the unit are these 2 pieces?

Figure C.7: The second page of the pre-test.

Probes and Follow-Up Questions :

Can you tell me more about why you did what you did in the case of...?

How come you put X blocks there?

etc...

C.5 Post-test questionnaire

A post-test, which included very similar questions to those of the pre-test, was given to each student after participating in the main experiment. The post-test questions maintained the same exercises as in the pre-test, differing only the numbers used in the exercises (Figures C.8 and C.9).

C.6 Log files

As mentioned in Chapter 6, Section 6.1.3.6, the Virtual Playground application was programmed to record each user's interaction with the system in the form of a text log file. Log files were collected only from the sessions of the interactive VR condition. Each log file recorded the:

- elapsed time from start of activity to end of activity
- time spent per element, i.e. per blocks of same colour
- time when switch to playground mode takes place
- number of blocks that were moved for each element (colour)
- total number of blocks moved in playground
- total number of feedback received for each of the feedback items (occupied tile, adjacent to other colour, next to fence, near bench, on footpath)

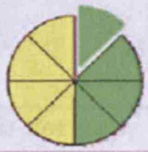
The log file did not record the user's position or navigation path in the environment, as this kind of information was not considered relevant. Figure C.10 presents an excerpt from a log file.

C.7 Participants' take-aways

Following completion of the study, a personalised gift bag was given to every child. The gift bag contained a laminated souvenir certificate of participation with the child's name (Figure C.11), a pair of glow-in-the-dark eyeglasses (specially selected to remind them of their experience of wearing the stereoglasses in the VR CAVE), a pencil with animals, a sharpener in the shape of a computer mouse, and bubbles (Figure C.12). The certificates were extremely successful with the kids, most of which exclaimed that they would hang theirs up in their room. The gifts were also highly appreciated, provoking many amusing comments (one child, for example, commented on the mouse sharpener being "wireless").

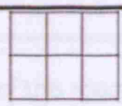
Post-test condition: ctrl | iVR | pVR

Name:__________________
Age :__________________



The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can! Don't worry if you cannot answer them all.

A1. Colour in $\frac{1}{3}$ of this grid:

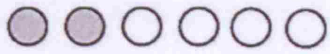


A2. Jill's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{3}$ of the cake to Jill and keep the rest for himself.

How many pieces of cake will he give to Jill? ______

A3.

How many circles do you see? ______

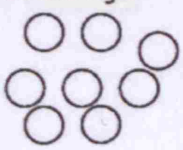


How many circles are shaded (grey)? ____

What fraction of the total is shaded?

____

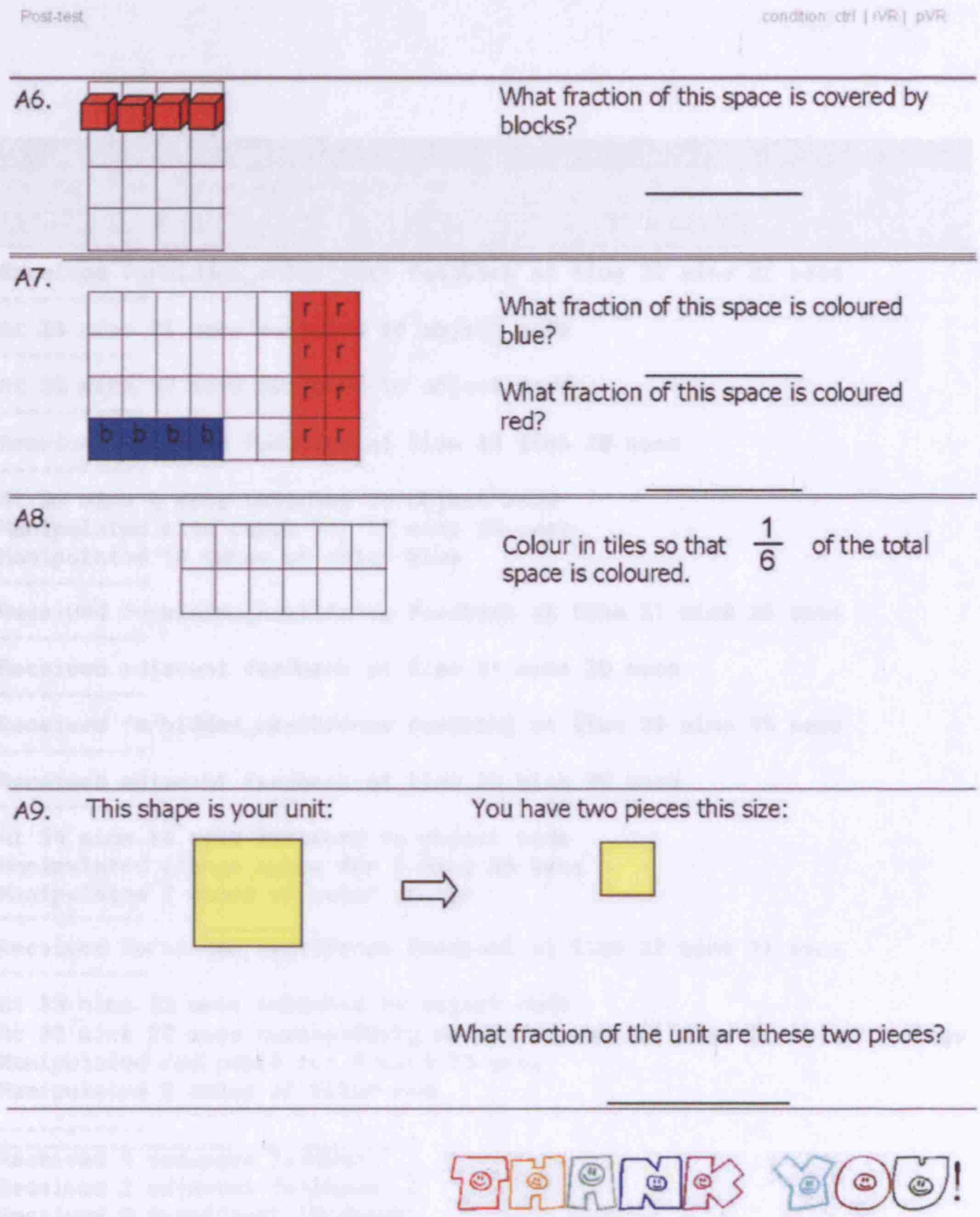
A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw half of them in the box on the right



A5. a. Circle the fraction that is larger: $\frac{1}{4}$ $\frac{1}{3}$

b. Circle the fraction that is smaller: $\frac{2}{3}$ $\frac{1}{4}$

Figure C.8: The first page of the post-test.



Post-test condition: ctrl | iVR | pVR

A6. What fraction of this space is covered by blocks?

____

A7. What fraction of this space is coloured blue?

____

What fraction of this space is coloured red?

____

A8. Colour in tiles so that $\frac{1}{6}$ of the total space is coloured.

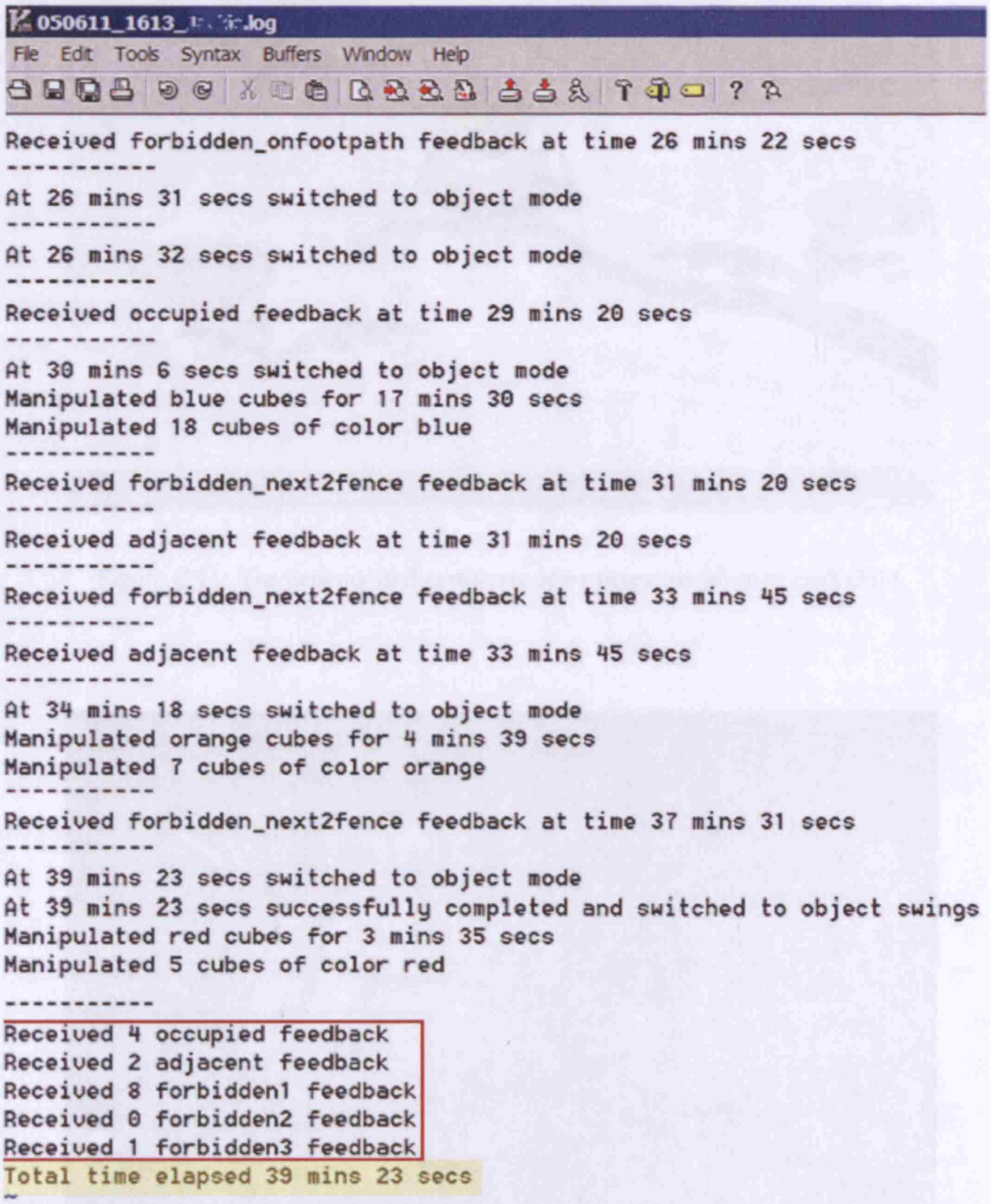
A9. This shape is your unit: You have two pieces this size:

What fraction of the unit are these two pieces?

____

THANK YOU!

Figure C.9: The second page of the post-test.




```
Received forbidden_onfootpath feedback at time 26 mins 22 secs
-----------
At 26 mins 31 secs switched to object mode
-----------
At 26 mins 32 secs switched to object mode
-----------
Received occupied feedback at time 29 mins 20 secs
-----------
At 30 mins 6 secs switched to object mode
Manipulated blue cubes for 17 mins 30 secs
Manipulated 18 cubes of color blue
-----------
Received forbidden_next2fence feedback at time 31 mins 20 secs
-----------
Received adjacent feedback at time 31 mins 20 secs
-----------
Received forbidden_next2fence feedback at time 33 mins 45 secs
-----------
Received adjacent feedback at time 33 mins 45 secs
-----------
At 34 mins 18 secs switched to object mode
Manipulated orange cubes for 4 mins 39 secs
Manipulated 7 cubes of color orange
-----------
Received forbidden_next2fence feedback at time 37 mins 31 secs
-----------
At 39 mins 23 secs switched to object mode
At 39 mins 23 secs successfully completed and switched to object swings
Manipulated red cubes for 3 mins 35 secs
Manipulated 5 cubes of color red

-----------
Received 4 occupied feedback
Received 2 adjacent feedback
Received 8 forbidden1 feedback
Received 0 forbidden2 feedback
Received 1 forbidden3 feedback
Total time elapsed 39 mins 23 secs
~
```

Figure C.10: Segment from an activity log file.

Figure C.11: The personalised certificate of participation given to each child.

Figure C.12: The gift pack given to each participant after completion of the study: a personalised laminated certificate of participation, a pair of glow-in-the-dark glasses, a pencil, a mouse-shaped sharpener, and bubbles.

C.8 Recruitment material and website

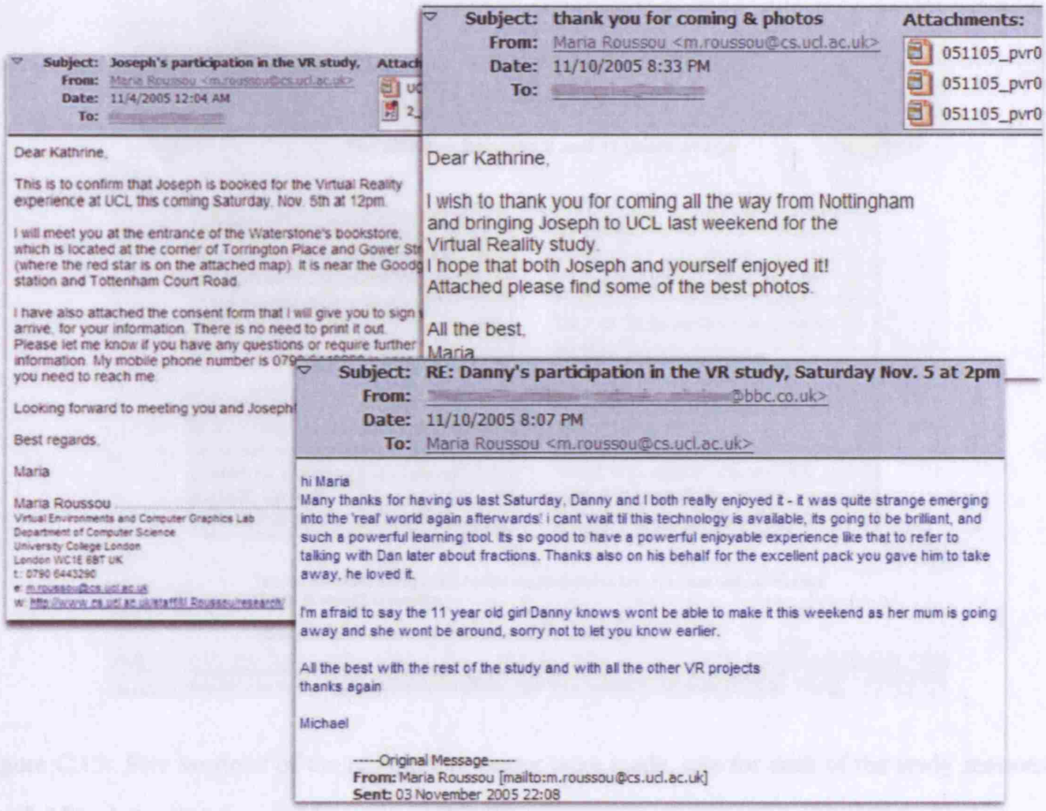
Electronic mail and verbal (telephone) communication were the primary methods of contacting schools, parents, and organisations that were judged as potential sources for recruiting children. Several meetings were also held, both at schools and with teachers who came at UCL for an in situ demonstration of the Virtual Playground and other VR programs in the virtual reality room.

A recruitment poster C.15 was designed and sent, along with the letter and information sheet (Figures C.1, C.2, and C.3), to all the above sources. Additionally, collaborating teachers in three different schools handed out the information to their students in maths class to take home. The poster was also mounted onto various information boards across campus and at student resident halls. This process took place at various times throughout the course of approximately one year, since the different conditions of the study were held at different times of the year. This was due to various reasons, including the availability and correct functioning of the VR equipment (which frequently presented technical failures), and timing the studies to maximise student participation (usually just before school holidays and during half-term). In any case, almost all studies were conducted on weekends when parents could bring their children into central London. Most parents followed the researcher's suggestion to combine their visit with a visit to the nearby British Museum.

Over 360 e-mails were exchanged between the researcher and participants' parents concerning recruitment, preparation for the study, detailed information for transportation and accessibility of the study location, post-study thank you notes, sending of photos (usually promised to the parents as an additional thank you for coming), and general communication (Figure C.13). E-mail communication with the parents was carried out on an individual basis with each (no mass mailing) in order to create a comfortable and trusting exchange, while each group was greeted near the university at a location of their choice (Figure C.14).

The researcher attended the annual BETT educational information and communications technologies event (http://www.bettshow.co.uk), where a number of companies and organisations were approached. Amongst these organisations, contact was made with the BBC's Factual and Learning division, and maintained throughout the duration of this research. As a result, a number of participants were recruited through the BBC's contacts with parents and students. NESTA Future Lab's Planet Science programme (http://www.planet-science.com) was also approached by the researcher and was given detailed information of the study in response to the editors' questions. A short call for the study along with a photo were finally included in their weekly e-newsletter, which is sent to about 15,000 teachers (primary and secondary), parents, students, and science communicators (Figure C.16).

During the final months of the study, a website with information about the research was created, collecting also all publications of the project (Figure C.18, C.17, C.19, and C.20). The goal of the website was twofold: to collect all information about the project into a concise and engaging presentation and to help in disseminating the project's needs at every stage (be it recruiting participants, making information available to teachers, crediting the people that supported the work). An additional benefit to the research occurred when the website won the Best Website award in the 2005 UCL Computer Science departmental



Subject: Joseph's participation in the VR study. Attach
From: Maria Roussou <m.roussou@cs.ucl.ac.uk>
Date: 11/4/2005 12:04 AM
To: [redacted]

Dear Kathrine,

This is to confirm that Joseph is booked for the Virtual Reality experience at UCL this coming Saturday, Nov. 5th at 12pm.

I will meet you at the entrance of the Waterstone's bookstore, which is located at the corner of Torrington Place and Gower St (where the red star is on the attached map). It is near the Goodg station and Tottenham Court Road.

I have also attached the consent form that I will give you to sign arrive, for your information. There is no need to print it out. Please let me know if you have any questions or require further information. My mobile phone number is 079[redacted] you need to reach me.

Looking forward to meeting you and Joseph

Best regards,

Maria

Maria Roussou
Virtual Environments and Computer Graphics Lab
Department of Computer Science
University College London
London WC1E 6BT UK
t: 0790 6443290
e: m.roussou@cs.ucl.ac.uk
w: http://www.cs.ucl.ac.uk/staff/M.Roussou/research/

Subject: thank you for coming & photos
From: Maria Roussou <m.roussou@cs.ucl.ac.uk>
Date: 11/10/2005 8:33 PM
To: [redacted]
Attachments: 051105_pvr0 051105_pvr0 051105_pvr0

Dear Kathrine,

I wish to thank you for coming all the way from Nottingham and bringing Joseph to UCL last weekend for the Virtual Reality study.
I hope that both Joseph and yourself enjoyed it!
Attached please find some of the best photos.

All the best,
Maria

Subject: RE: Danny's participation in the VR study, Saturday Nov. 5 at 2pm
From: [redacted]@bbc.co.uk>
Date: 11/10/2005 8:07 PM
To: Maria Roussou <m.roussou@cs.ucl.ac.uk>

hi Maria
Many thanks for having us last Saturday, Danny and I both really enjoyed it - it was quite strange emerging into the 'real' world again afterwards! i cant wait til this technology is available, its going to be brilliant, and such a powerful learning tool. its so good to have a powerful enjoyable experience like that to refer to talking with Dan later about fractions. Thanks also on his behalf for the excellent pack you gave him to take away, he loved it.

I'm afraid to say the 11 year old girl Danny knows wont be able to make it this weekend as her mum is going away and she wont be around, sorry not to let you know earlier.

All the best with the rest of the study and with all the other VR projects
thanks again

Michael

-----Original Message-----
From: Maria Roussou [mailto:m.roussou@cs.ucl.ac.uk]
Sent: 03 November 2005 22:08

Figure C.13: A sample of the e-mail communication with parents. Over 360 e-mails were exchanged between the researcher and participants' parents throughout the duration of the study.

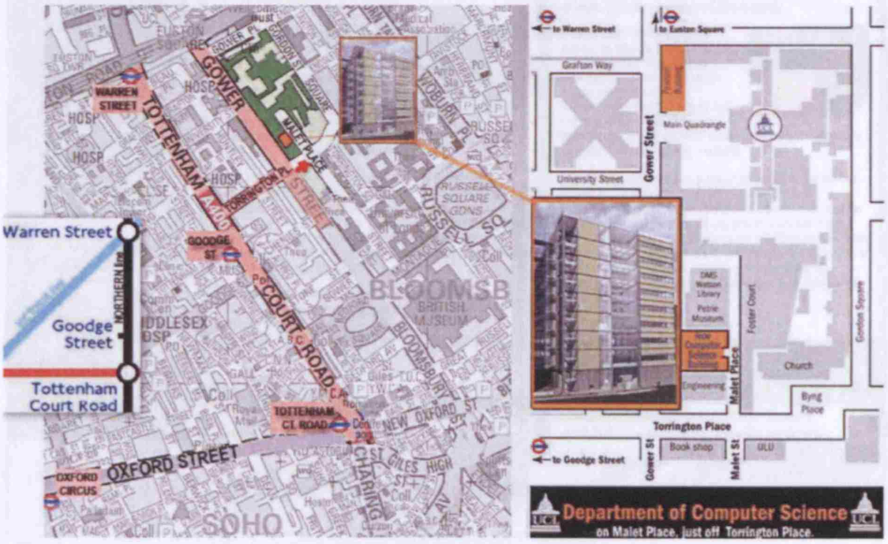


Figure C.14: As studies took place on weekends when access to the university building was restricted, participants were greeted at either the entrance of a nearby bookstore (shown on the map with a red star) or at the nearest metro station.

Figure C.15: Five versions of the recruitment poster were made, one for each of the study sessions in April, May, June, October, and November of 2005.

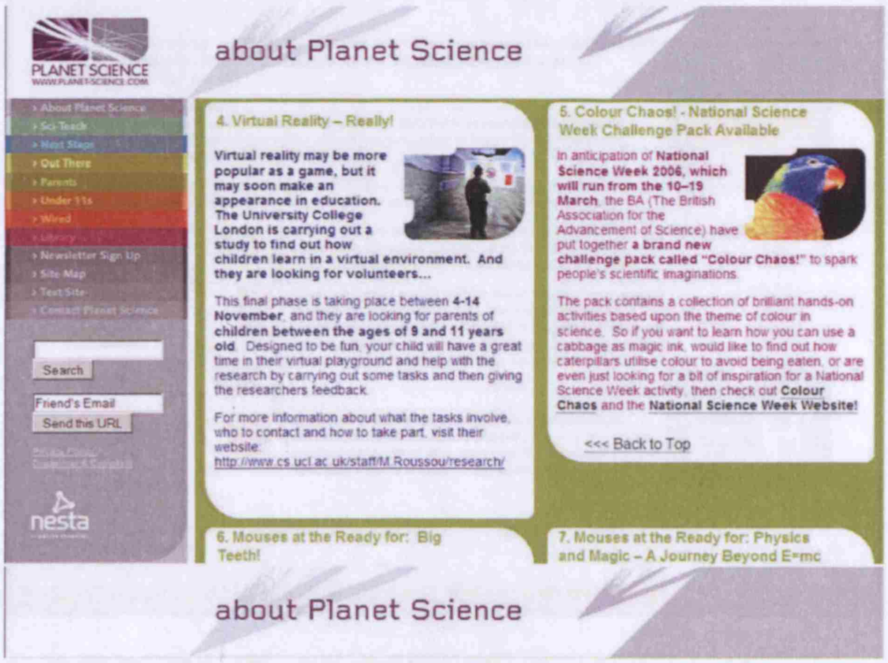
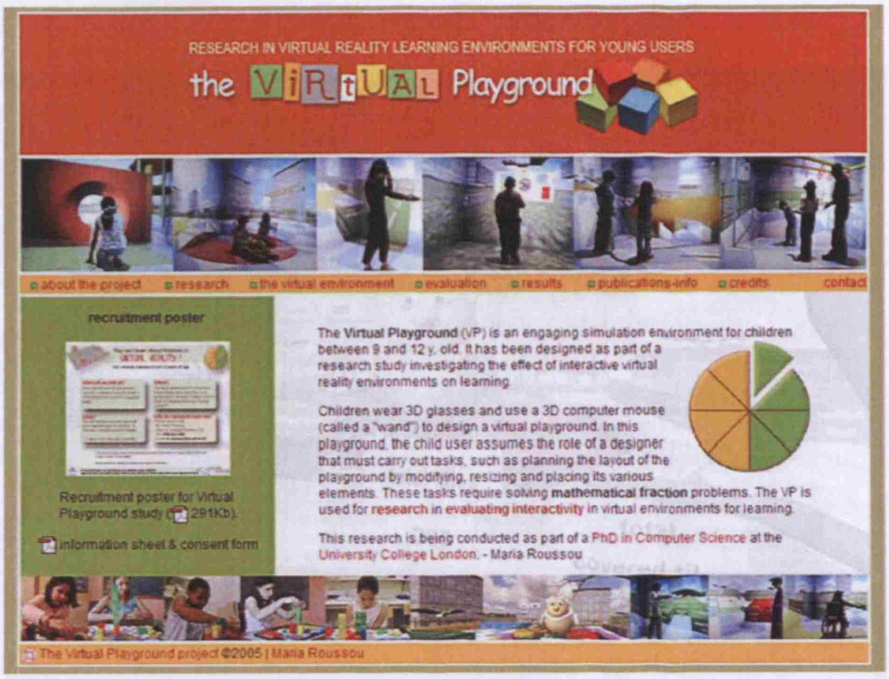


Figure C.16: Issue 153 (October 7, 2005) of the NESTA Future Lab's Planet Science Newsletter aided the recruitment process by including a column titled "Virtual Reality Really!"

research web pages competition, sponsored by *searchspace*. The first prize translated into a monetary award of £550, which was used to cover the expenses for the participant's gifts (Figure C.12) and travel expenses (in some cases parents came all the way from Nottingham and Brighton).

Figure C.17: The Virtual Playground webpage describing the design of the environment.



RESEARCH IN VIRTUAL REALITY LEARNING ENVIRONMENTS FOR YOUNG USERS

the ViRtUAL Playground

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recruitment poster

Recruitment poster for Virtual Playground study (291Kb).

information sheet & consent form

The **Virtual Playground** (VP) is an engaging simulation environment for children between 9 and 12 y. old. It has been designed as part of a research study investigating the effect of interactive virtual reality environments on learning.

Children wear 3D glasses and use a 3D computer mouse (called a "wand") to design a virtual playground. In this playground, the child user assumes the role of a designer that must carry out tasks, such as planning the layout of the playground by modifying, resizing and placing its various elements. These tasks require solving **mathematical fraction** problems. The VP is used for research in evaluating interactivity in virtual environments for learning.

This research is being conducted as part of a PhD in Computer Science at the University College London. - Maria Roussou

The Virtual Playground project ©2005 | Maria Roussou

RESEARCH IN VIRTUAL REALITY LEARNING ENVIRONMENTS FOR YOUNG USERS

the ViRtUAL Playground

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The basic objective of this research is to investigate user interaction in virtual environments (VEs). Specifically, the main research question of this study examines the effect that **interactivity**, as one of the essential properties of computer-based learning environments, may have in the formation of children's conceptual learning.

Research context and motivation

Virtual Reality (VR), regarded here as the three-dimensional multi-sensory immersive and interactive digital environment, has triggered public imagination as the dominant technological metaphor for the way our work, education, and leisure may be delivered in the future. While VR has yet to become a widespread technology, there has, in fact, been a proliferation of VR installations (in the form of exhibits) and applications (in the form of "experiences") available to and accessible by the public.

The entertainment market is usually the first to embrace current technological achievements to attract and motivate visitors. Other public settings, such as museums and informal educational institutions, are generally known to be hesitant in adopting cutting-edge digital technologies. However, even these are now considering various forms of VR as a means to attract and motivate visitors but also in an attempt to deliver their educational agenda more effectively [5]. Considering the plethoric development of interactive systems at large, it may not be long before VR installations and applications make their way into the schools and the home.

Does interactivity enable learners to construct meaning?

For virtual environments, the techniques for developing interactivity, regarded as the process with which users can act upon and even modify a virtual world, are relatively unexplored. Yet, interactivity is being promoted widely, not only for its recreational potential but also for its significance for learning. This is even more prominent in the case of VR, since interactivity is largely regarded as one of the medium's essential properties. The immediate implication which can be drawn from studying related literature is the common belief that a virtual learning environment is more effective if it is interactive. However, little systematic research is available to provide evidence that interactive learning environments in VR can bring "added value" to learning, especially in children. Furthermore, it is not certain if interactivity alone, as an essential property of the virtual reality medium, can provide a strong effect upon learning. Most research in VR is focused on the immersive properties of the medium (for example, the sense of presence). Similarly, previous research into the use of VR in education has concentrated on training applications rather than conceptual learning.

A conceptual learning problem represented in VR

In order to examine interactivity and exploit the capabilities of the VR medium in visualizing abstract and difficult conceptual learning problems and providing feedback, we chose the learning domain of fractions. We created an experimental VE in which children are asked to complete constructivist tasks that are designed as mathematical fraction problems. Fractions were chosen as the learning topic due to the difficulty that primary school students have in understanding and connecting them to real-world situations. In other words, fractions lend themselves to designing learning tasks that are, at the same time, conceptually difficult, abstract enough to justify representation via a VR simulation of a real-world situation, and can allow for a kind of varied and incremental interactive treatment. We used this environment to evaluate our hypotheses about interactivity.

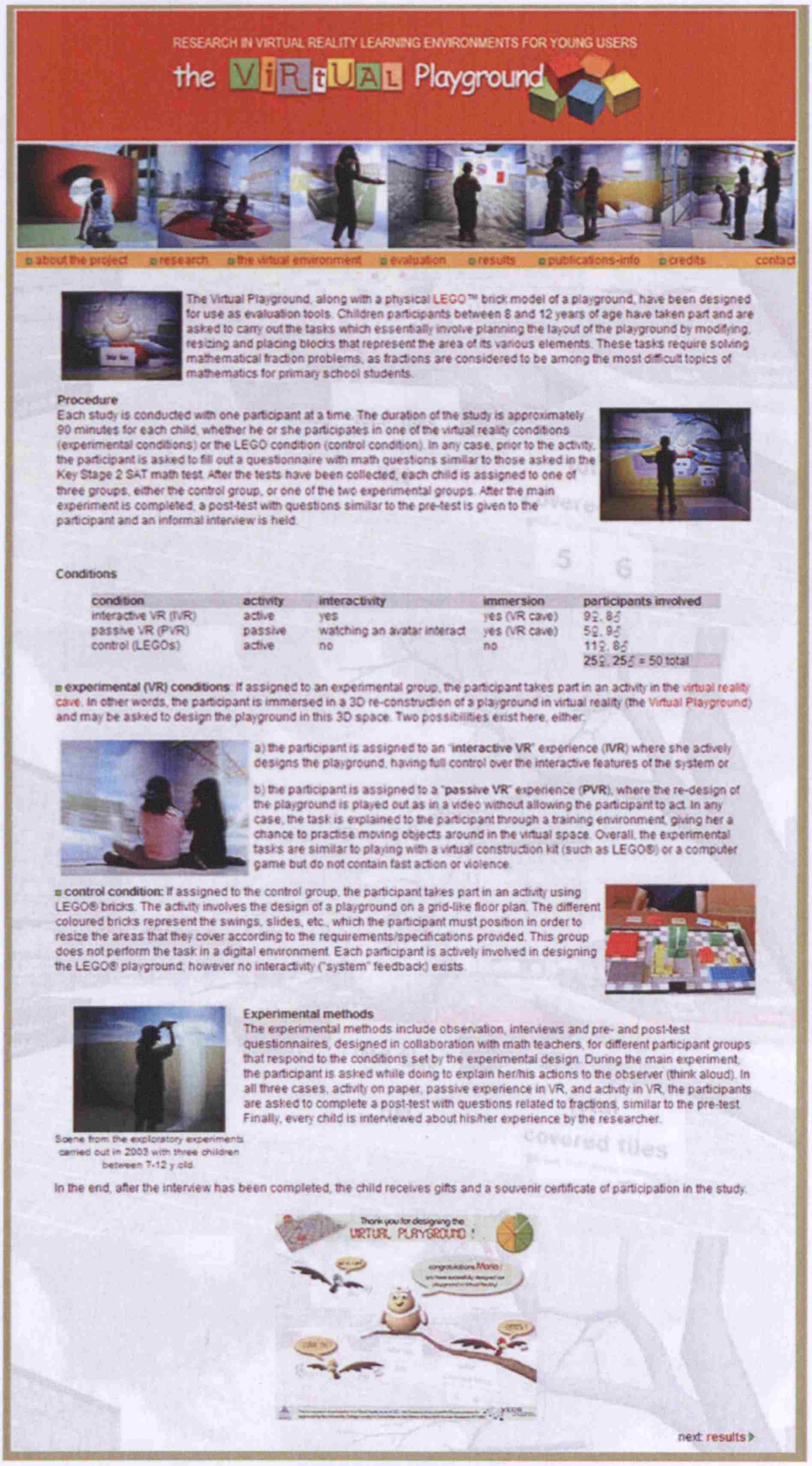
see also Publications

Previous related research in VR and informal education

next the virtual environment

The Virtual Playground project ©2005 | Maria Roussou

Figure C.18: The home page and the "Research" page of the Virtual Playground website, accessible at www.cs.ucl.ac.uk/staff/M.Roussou/research/.



RESEARCH IN VIRTUAL REALITY LEARNING ENVIRONMENTS FOR YOUNG USERS

the ViRtUAL Playground

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The Virtual Playground, along with a physical LEGO™ brick model of a playground, have been designed for use as evaluation tools. Children participants between 8 and 12 years of age have taken part and are asked to carry out the tasks which essentially involve planning the layout of the playground by modifying, resizing and placing blocks that represent the area of its various elements. These tasks require solving mathematical fraction problems, as fractions are considered to be among the most difficult topics of mathematics for primary school students.

Procedure

Each study is conducted with one participant at a time. The duration of the study is approximately 90 minutes for each child, whether he or she participates in one of the virtual reality conditions (experimental conditions) or the LEGO condition (control condition). In any case, prior to the activity, the participant is asked to fill out a questionnaire with math questions similar to those asked in the Key Stage 2 SAT math test. After the tests have been collected, each child is assigned to one of three groups, either the control group, or one of the two experimental groups. After the main experiment is completed, a post-test with questions similar to the pre-test is given to the participant and an informal interview is held.

Conditions

condition	activity	interactivity	immersion	participants involved
interactive VR (IVR)	active	yes	yes (VR cave)	9♀, 8♂
passive VR (PVR)	passive	watching an avatar interact	yes (VR cave)	5♀, 9♂
control (LEGOs)	active	no	no	11♀, 8♂
				25♀, 25♂ = 50 total

experimental (VR) conditions: If assigned to an experimental group, the participant takes part in an activity in the virtual reality cave. In other words, the participant is immersed in a 3D re-construction of a playground in virtual reality (the Virtual Playground) and may be asked to design the playground in this 3D space. Two possibilities exist here, either:

a) the participant is assigned to an "**interactive VR**" experience (**IVR**) where she actively designs the playground, having full control over the interactive features of the system or

b) the participant is assigned to a "**passive VR**" experience (**PVR**), where the re-design of the playground is played out as in a video without allowing the participant to act. In any case, the task is explained to the participant through a training environment, giving her a chance to practise moving objects around in the virtual space. Overall, the experimental tasks are similar to playing with a virtual construction kit (such as LEGO®) or a computer game but do not contain fast action or violence.

control condition: If assigned to the control group, the participant takes part in an activity using LEGO® bricks. The activity involves the design of a playground on a grid-like floor plan. The different coloured bricks represent the swings, slides, etc., which the participant must position in order to resize the areas that they cover according to the requirements/specifications provided. This group does not perform the task in a digital environment. Each participant is actively involved in designing the LEGO® playground; however no interactivity ("system" feedback) exists.

Experimental methods

The experimental methods include observation, interviews and pre- and post-test questionnaires, designed in collaboration with math teachers, for different participant groups that respond to the conditions set by the experimental design. During the main experiment, the participant is asked while doing to explain her/his actions to the observer (think aloud). In all three cases, activity on paper, passive experience in VR, and activity in VR, the participants are asked to complete a post-test with questions related to fractions, similar to the pre-test. Finally, every child is interviewed about his/her experience by the researcher.

Scene from the exploratory experiments carried out in 2003 with three children between 7-12 y old.

In the end, after the interview has been completed, the child receives gifts and a souvenir certificate of participation in the study.

next results ▸

Figure C.19: The "Evaluation" page of the Virtual Playground website.

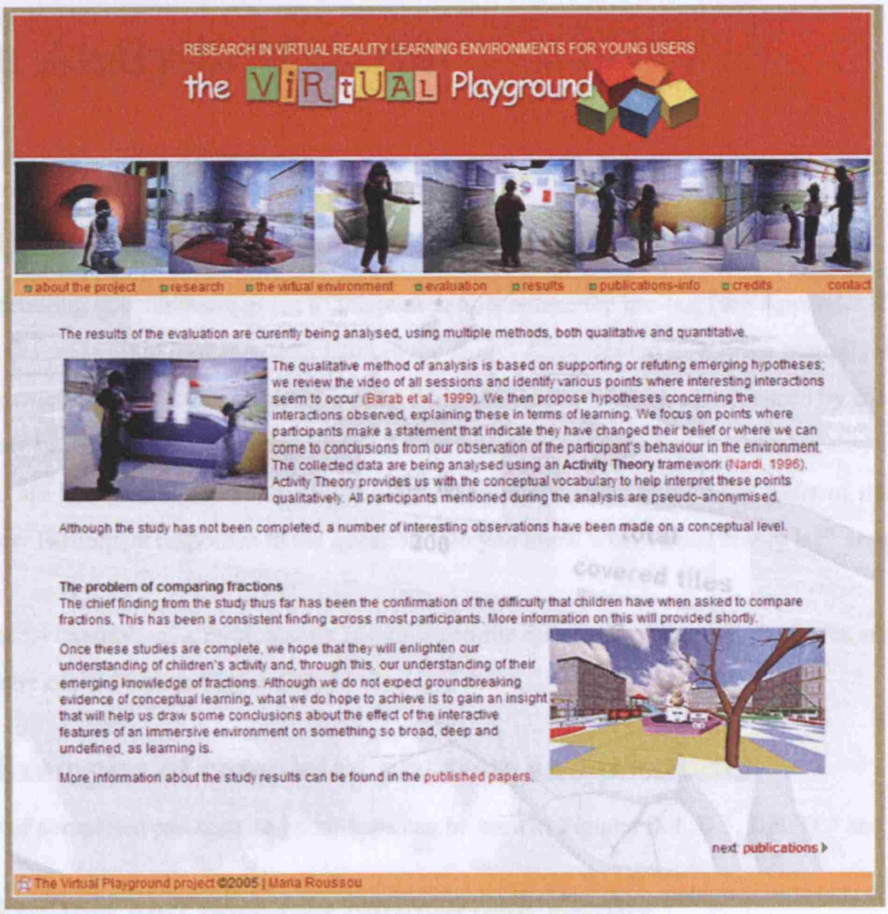


Figure C.20: The "Results" page of the Virtual Playground website.

Appendix D

Main Analysis Material

D.1 Demographics and profiling information

The user profiling questionnaire given to the participants before the pre-test (see Appendix C) aimed at creating a general profile for each participant in the study. As presented in 7.1, the majority of the children that participated in the main study reported a high computer literacy, as evidenced by the frequency of computer usage and game playing, and had a pre-existing notion of what virtual reality is, through television, 3D films at science musuems and entertainment venues, and on the basis of their gaming experiences. Participant responses to the question "Do you know what virtual reality is?" are grouped in Table D.1.

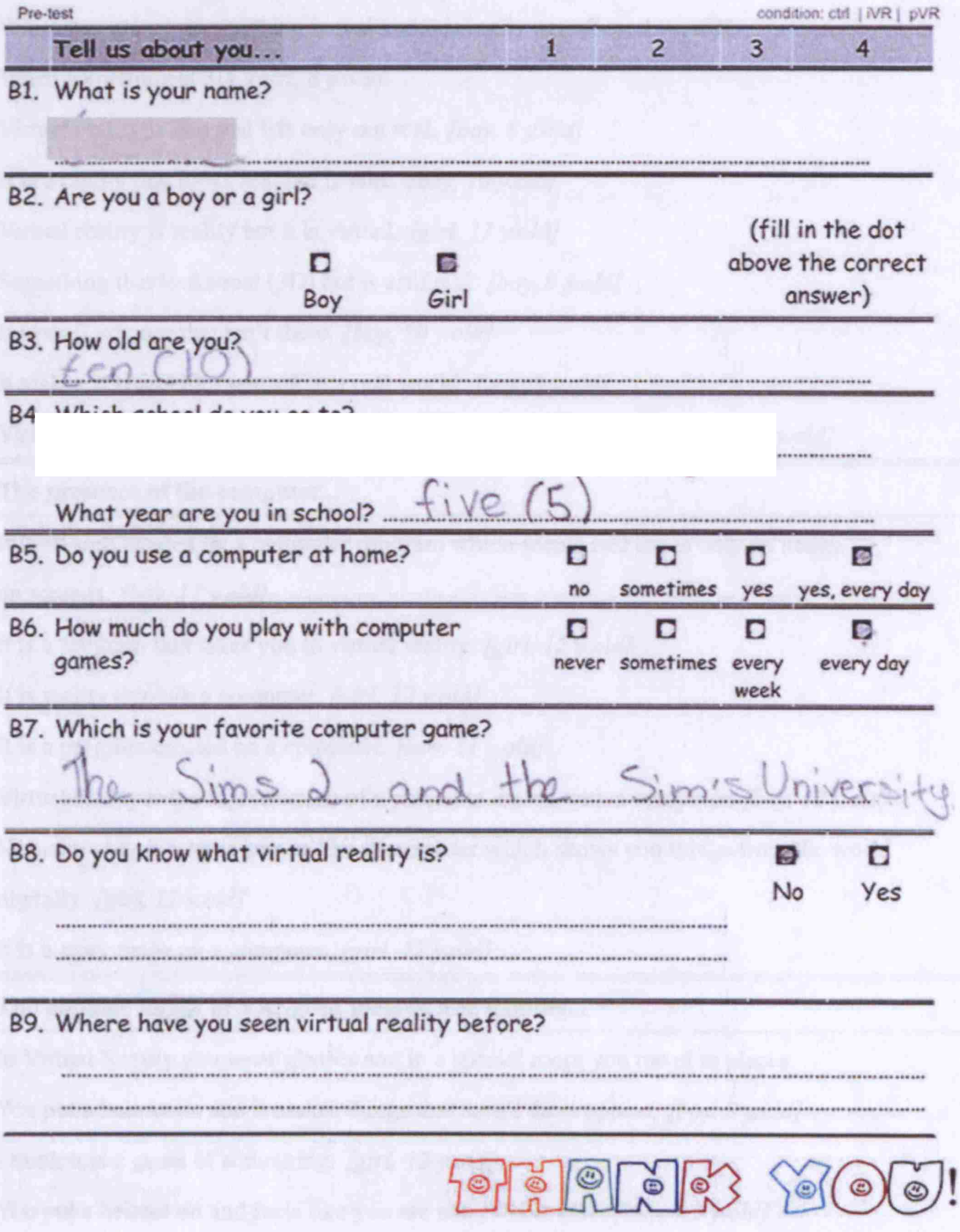
A typical example of a participant's responses to the questions of the demographics and profiling questionnaire can be seen in Figure D.2.

D.2 Examples of completed pre-tests and post-tests

Examples of completed pre-tests and post-tests can be seen in Figures D.4, D.5, D.6, D.7 and D.8.

D.3 Pre-test and post-test comparison results

Figures D.9, D.10, and D.11 detail the responses from each participant in the IVR, PVR, and LEGO conditions respectively. The first column lists the participant id (condition, number, gender 'b' or 'g', and age). The following 11 columns list the questions of the pre-test, then the total number of correct responses (total number of 'T' per participant) and the aptitude categorisation (0 - 6 is low, 7-9 is medium and 10-11 is high. The columns that follow list the responses to the post-test and the total number of correct responses and aptitude accordingly. The final column on the right indicates whether there was an increase (1) in the participant's score between her pre-test and post-test responses, a decrease (-1), or no change.



Pre-test condition: ctrl | iVR | pVR

Tell us about you...	1	2	3	4

B1. What is your name?

[redacted]

B2. Are you a boy or a girl?

☐ Boy ■ Girl (fill in the dot above the correct answer)

B3. How old are you? ten (10)

B4. Which school do you go to? [redacted]

What year are you in school? five (5)

B5. Do you use a computer at home? ☐ no ☐ sometimes ☐ yes ■ yes, every day

B6. How much do you play with computer games? ☐ never ☐ sometimes ☐ every week ■ every day

B7. Which is your favorite computer game?

The Sims 2 and the Sim's University

B8. Do you know what virtual reality is? ■ No ☐ Yes

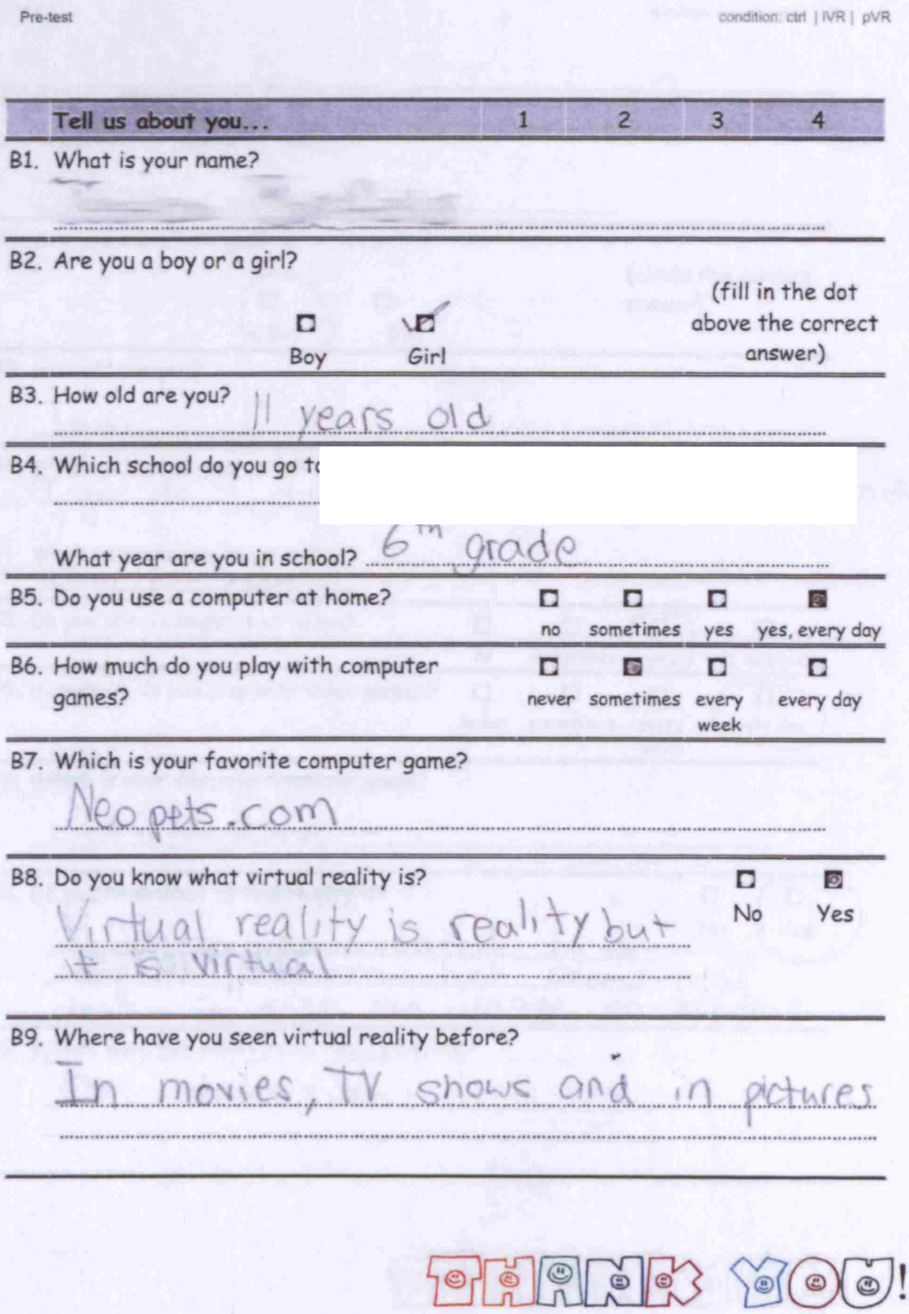
B9. Where have you seen virtual reality before?

THANK YOU!

Figure D.1: One of the children's responses to the profiling questions.

Like reality, but really not...
You see places and think you are there, it is very real. *[boy, 12 y.old]*
It is something people do with their imagination but it looks real. *[girl, 11 y.old]*
It is like fake reality. *[boy, 12 y.old]*
When you are sure something is real and it is really not. *[boy, 11 y.old]*
When something is 3D. *[girl, 8 y.old]*
Virtual reality is like real life only not real. *[boy, 8 y.old]*
It is a reality that looks real but is fake. *[boy, 10 y.old]*
Virtual reality is reality but it is virtual. *[girl, 11 y.old]*
Something that looks real (3D) but is artificial. *[boy, 9 y.old]*
It is stuff you see that isn't there. *[boy, 10 y.old]*
It makes you feel like you are in a real world. *[boy, 9 y.old]*
Virtual reality is a small space that makes you think you are there. *[boy, 11 y.old]*
The presence of the computer...
It is an area created by a computer program which seems real but is only an image on screens. *[boy, 11 y.old]*
It is a program that takes you to virtual reality. *[girl, 12 y.old]*
It is reality through a computer. *[girl, 12 y.old]*
It is a program created on a computer. *[boy, 11 y.old]*
Virtual reality is the reproduction of a place but drawn with a computer. *[boy, 12 y.old]*
Virtual reality is a large screen like a computer which shows you things from the world digitally. *[girl, 12 y.old]*
It is a story made on a computer. *[girl, 12 y.old]*
The popular image of VR: gear, glasses, and gaming...
In Virtual Reality you wear glasses and in a special room you travel to places.
You put a helmet on and it makes things that aren't there appear. *[boy, 9 y.old]*
I think it is a game of something. *[girl, 12 y.old]*
You put a helmet on and feels like you are somewhere else. *[boy, 9.5 y.old]*
It is a projection with images from reality. I've seen it with special glasses. *[girl, 11 y.old]*
To see you have to wear special glasses. It is pictures that look like they're real. *[girl, 12 y.old]*
Like a DVD/Computer game. *[boy, 8 y.old]*

Table D.1: Selected responses to question B8 ("Do you know what virtual reality is?") of the user profiling questionnaire given to the participants before the pre-test (see Appendix C, C.5). The responses are roughly grouped according to underlying themes.

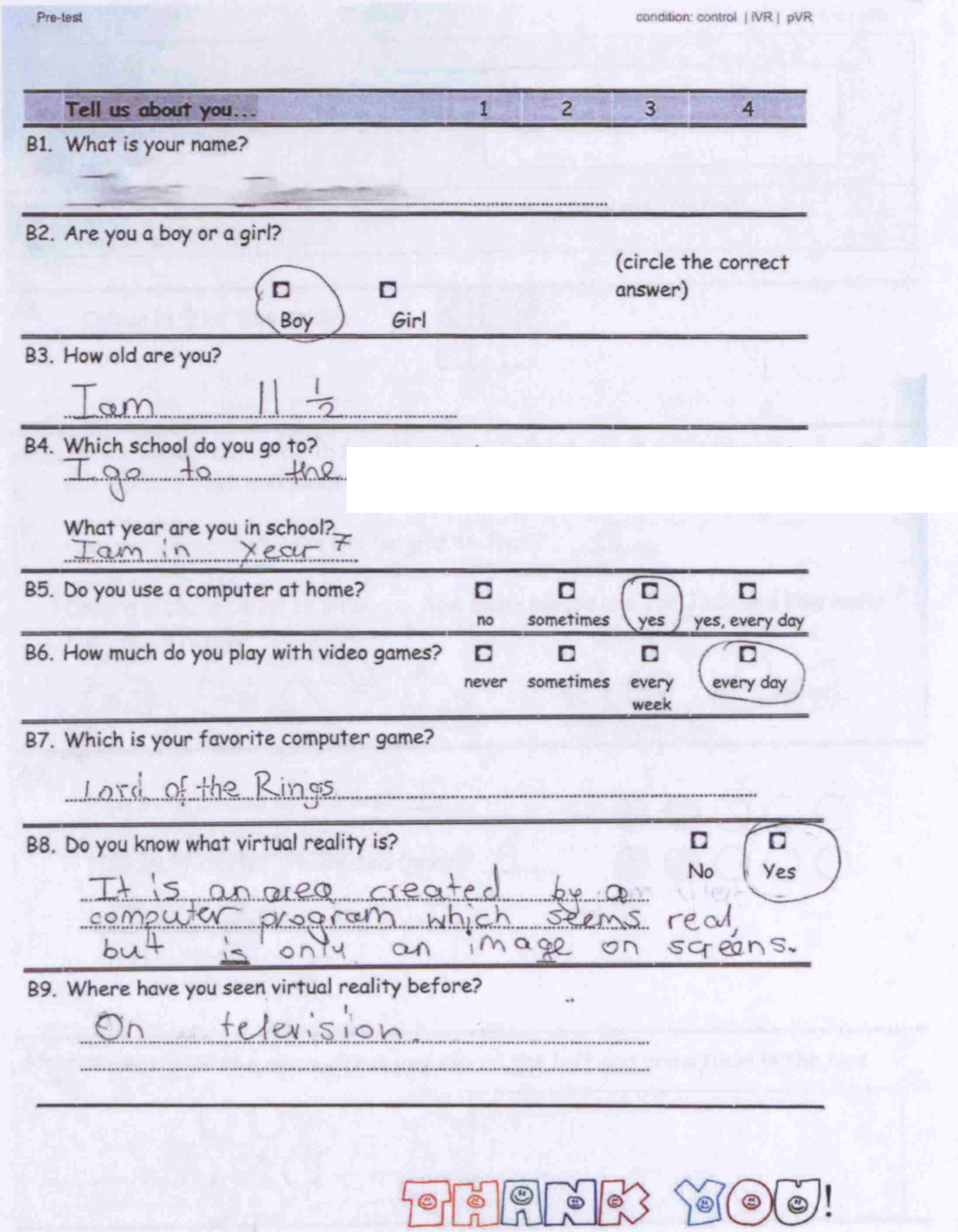


Pre-test condition: ctrl | IVR | pVR

Tell us about you...	1	2	3	4
B1. What is your name?				
B2. Are you a boy or a girl? (fill in the dot above the correct answer)	Boy	Girl ✓		
B3. How old are you? 11 years old				
B4. Which school do you go t…				
What year are you in school? 6th grade				
B5. Do you use a computer at home?	no	sometimes	yes	yes, every day ■
B6. How much do you play with computer games?	never	sometimes ■	every week	every day
B7. Which is your favorite computer game? Neopets.com				
B8. Do you know what virtual reality is? Virtual reality is reality but it is virtual	No	Yes ■		
B9. Where have you seen virtual reality before? In movies, TV shows and in pictures				

THANK YOU!

Figure D.2: One of the children's responses to the profiling questions.

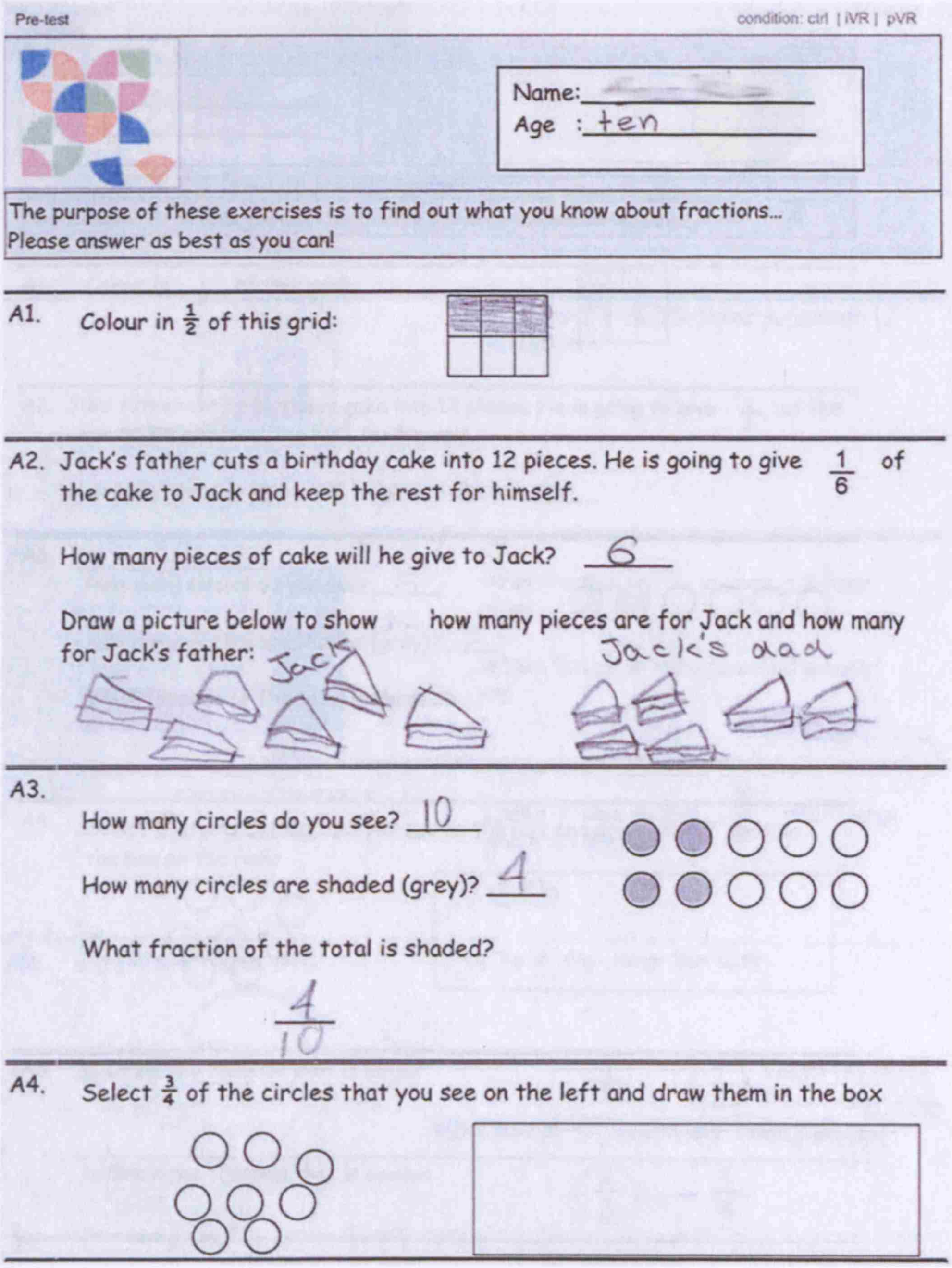


Pre-test condition: control | iVR | pVR

Tell us about you...	1	2	3	4
B1. What is your name? [redacted]				
B2. Are you a boy or a girl? (circle the correct answer) Boy Girl				
B3. How old are you? I am 11 ½				
B4. Which school do you go to? I go to the [redacted] What year are you in school? I am in Year 7				
B5. Do you use a computer at home?	no	sometimes	yes	yes, every day
B6. How much do you play with video games?	never	sometimes	every week	every day
B7. Which is your favorite computer game? Lord of the Rings				
B8. Do you know what virtual reality is? It is an area created by a computer program which seems real, but is only an image on screens.			No	Yes
B9. Where have you seen virtual reality before? On television.				

THANK YOU!

Figure D.3: One of the children's responses to the profiling questions.



Pre-test

condition: ctrl | iVR | pVR

Name:

Age : ten

The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can!

A1. Colour in $\frac{1}{2}$ of this grid:

A2. Jack's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{6}$ of the cake to Jack and keep the rest for himself.

How many pieces of cake will he give to Jack? 6

Draw a picture below to show how many pieces are for Jack and how many for Jack's father:

Jack

Jack's dad

A3.

How many circles do you see? 10

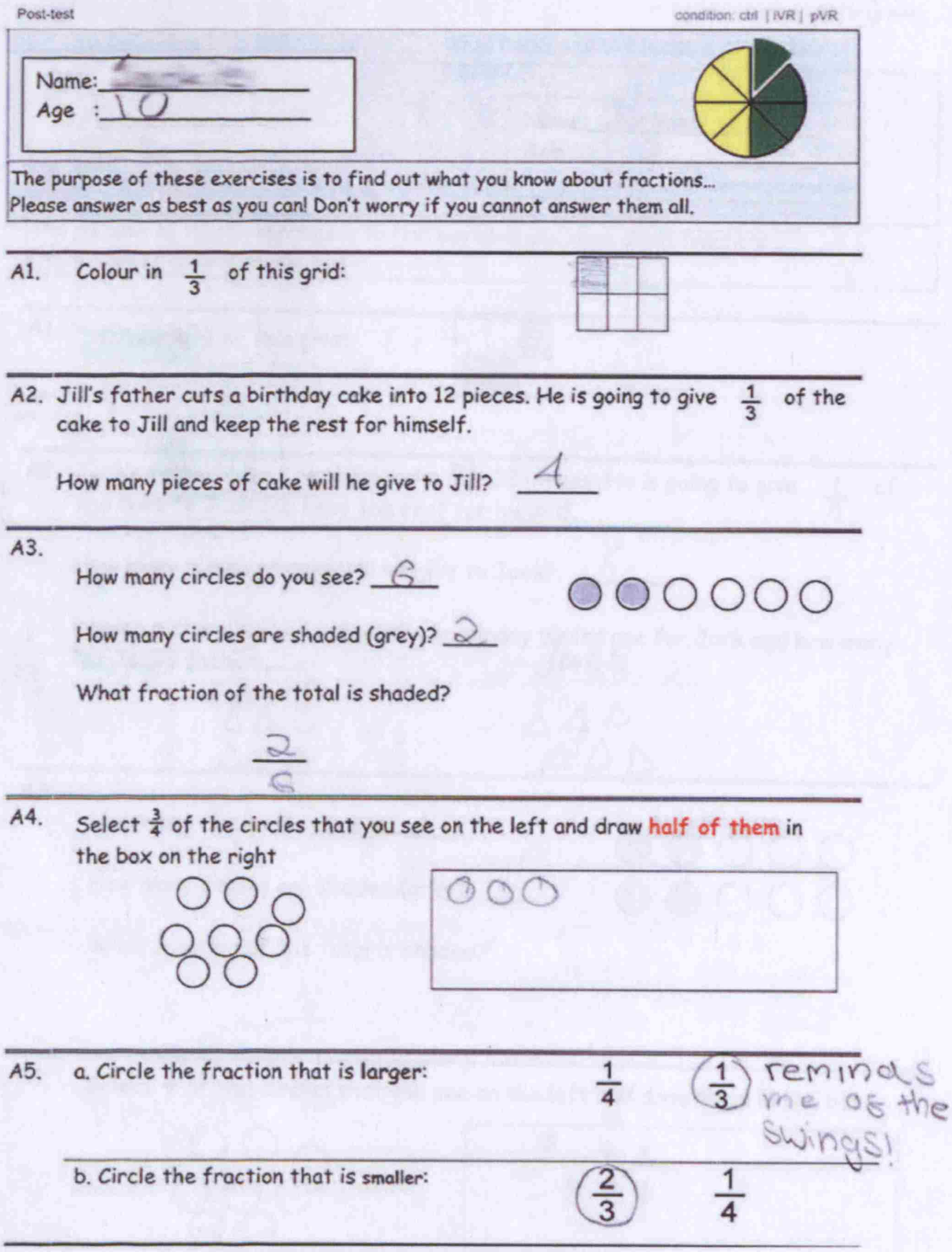
How many circles are shaded (grey)? 4

What fraction of the total is shaded?

$\frac{4}{10}$

A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw them in the box

Figure D.4: One of the children's responses to the pre-test.


Post-test

condition: ctrl | iVR | pVR

Name:
Age : 10

The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can! Don't worry if you cannot answer them all.

A1. Colour in $\frac{1}{3}$ of this grid:

A2. Jill's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{3}$ of the cake to Jill and keep the rest for himself.

How many pieces of cake will he give to Jill? 4

A3.

How many circles do you see? 6

How many circles are shaded (grey)? 2

What fraction of the total is shaded?

$\frac{2}{6}$

A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw half of them in the box on the right

A5. a. Circle the fraction that is larger: $\frac{1}{4}$ $\frac{1}{3}$ reminds me of the swings!

b. Circle the fraction that is smaller: $\frac{2}{3}$ $\frac{1}{4}$

Figure D.5: One of the children's responses to the post-test.

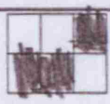
Pre-test

condition: ~~cd~~ | IVR ~~pVR~~

Name: [redacted]
Age : 8

The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can!

A1. Colour in $\frac{1}{2}$ of this grid:



A2. Jack's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{6}$ of the cake to Jack and keep the rest for himself.

How many pieces of cake will he give to Jack? 6

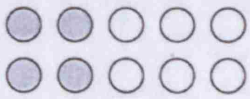
Draw a picture below to show the how many pieces are for Jack and how many for Jack's father:

Father △△△ △△△   Jack △△△ △△△

A3.

How many circles do you see? 10

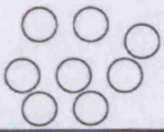
How many circles are shaded (grey)? 4



What fraction of the total is shaded?

$\frac{1}{4}$

A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw them in the box



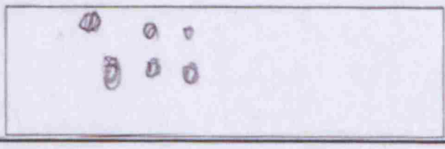
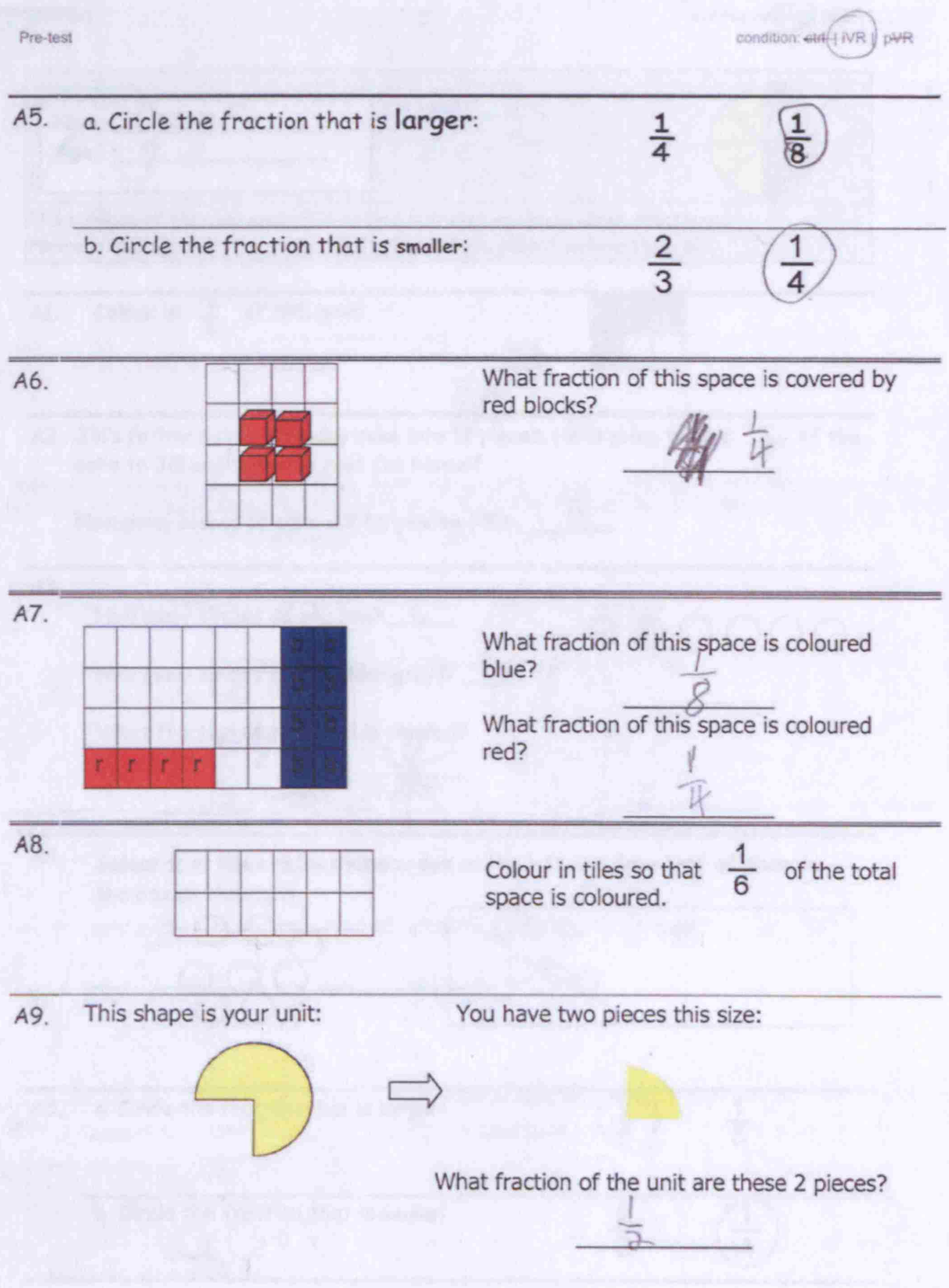


Figure D.6: One of the children's responses to the pre-test.



Pre-test condition: ~~ctrl~~ | IVR | ~~pVR~~

A5. a. Circle the fraction that is **larger**: $\frac{1}{4}$ $\frac{1}{8}$

b. Circle the fraction that is smaller: $\frac{2}{3}$ $\frac{1}{4}$

A6. What fraction of this space is covered by red blocks? $\frac{1}{4}$

A7. What fraction of this space is coloured blue? $\frac{1}{8}$

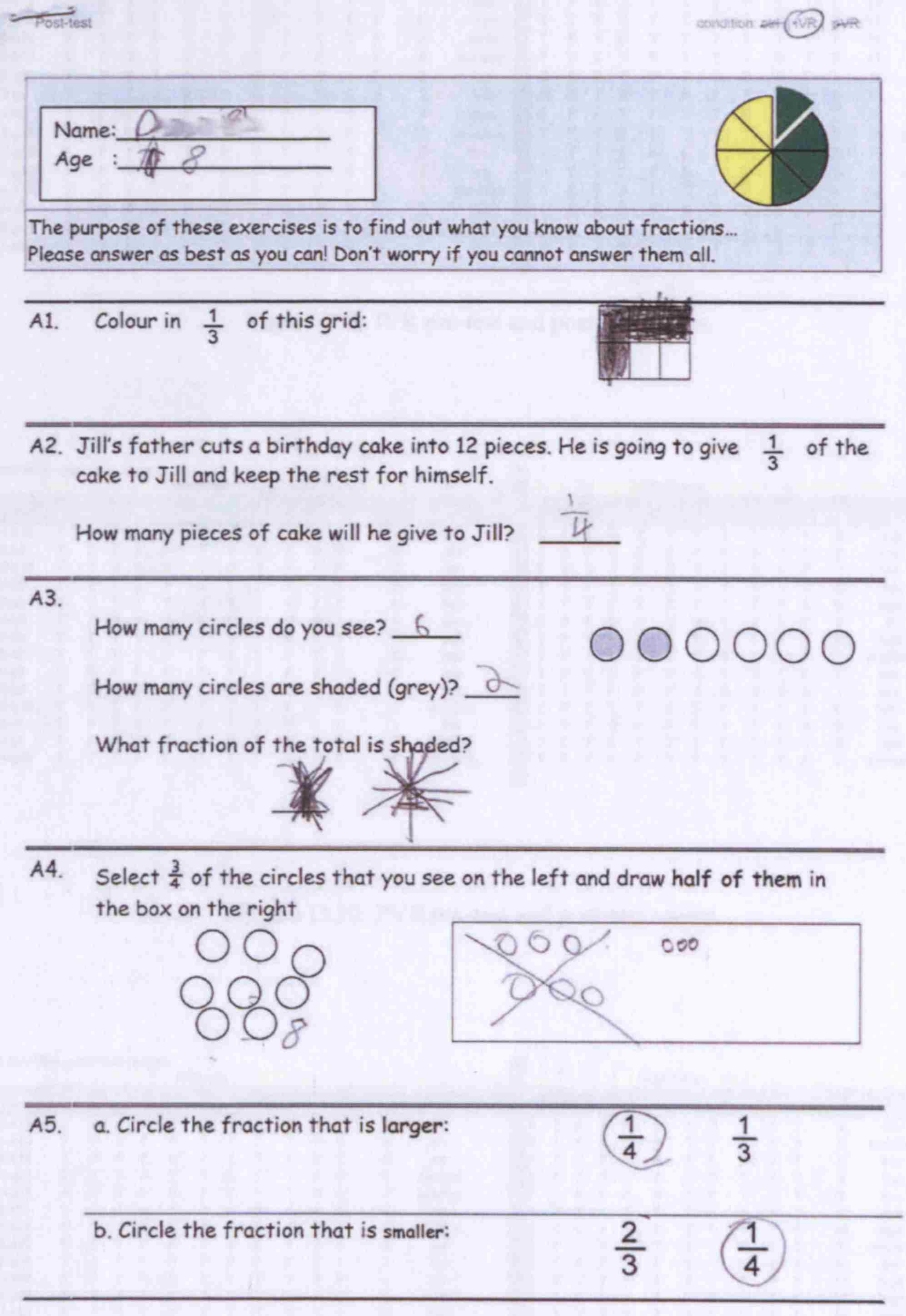
What fraction of this space is coloured red? $\frac{1}{4}$

A8. Colour in tiles so that $\frac{1}{6}$ of the total space is coloured.

A9. This shape is your unit: You have two pieces this size:

What fraction of the unit are these 2 pieces? $\frac{1}{2}$

Figure D.7: One of the children's responses to the pre-test.



Post-test

condition: ~~ael~~ tVR svR

Name:

Age : 8

The purpose of these exercises is to find out what you know about fractions...
Please answer as best as you can! Don't worry if you cannot answer them all.

A1. Colour in $\frac{1}{3}$ of this grid:

A2. Jill's father cuts a birthday cake into 12 pieces. He is going to give $\frac{1}{3}$ of the cake to Jill and keep the rest for himself.

How many pieces of cake will he give to Jill? $\frac{1}{4}$

A3.

How many circles do you see? 6

How many circles are shaded (grey)? 2

What fraction of the total is shaded?

A4. Select $\frac{3}{4}$ of the circles that you see on the left and draw **half** of them in the box on the right

8

A5. a. Circle the fraction that is larger: $\frac{1}{4}$ $\frac{1}{3}$

b. Circle the fraction that is smaller: $\frac{2}{3}$ $\frac{1}{4}$

Figure D.8: One of the children's responses to the post-test.

IVR condition - participant scores

	PRE-test													POST-test													
id	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	change
IVR01-b11	T	T	T	T	T	F	T	T	T	T	F	9	medium	T	T	T	T	T	F	T	T	T	T	F	9	medium	0
IVR02-g12	F	T	T	F	F	T	T	T	T	F	T	7	medium	T	F	T	F	T	T	T	T	T	F	F	7	medium	0
IVR03-b9	T	0	T	0	F	F	0	0	0	0	0	2	low	F	0	0	0	F	0	0	0	0	0	0	0	low	-1
IVR04-b12	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	T	T	T	11	high	0
IVR05-g12	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	T	T	T	11	high	0
IVR06-b10	T	T	T	T	T	T	T	T	T	T	F	10	high	T	T	T	F	T	T	T	T	T	T	T	10	high	0
IVR07-b11	T	T	T	T	T	T	T	F	F	T	F	8	medium	T	T	T	T	T	T	T	T	T	T	T	11	high+	1
IVR08-g9	T	T	0	T	T	T	0	0	0	0	F	5	low	0	0	F	T	T	T	0	0	0	F	T	4	low	-1
IVR09-g9	T	F	T	0	F	F	0	0	0	F	0	2	low	F	T	T	0	T	F	T	T	0	F	T	6	low	1
IVR10-b8	T	F	F	T	F	T	T	F	F	0	F	4	low	F	F	F	T	F	T	T	F	F	T	T	5	low	1
IVR11-g10	T	F	T	F	T	T	T	T	T	F	F	7	medium	T	T	T	F	T	T	T	T	0	T	T	9	medium+	1
IVR12-g10	T	F	T	F	T	F	T	T	T	0	F	6	low	T	T	T	F	F	F	T	F	F	T	T	6	low	0
IVR13-g10	T	F	T	0	F	F	T	T	T	0	0	5	low	F	T	T	T	T	F	T	T	T	T	T	9	medium+	1
IVR14-b10	T	F	T	T	F	T	T	F	F	T	T	7	medium	T	T	T	F	T	T	T	T	T	T	T	10	high+	1
IVR15-g7	T	0	0	0	F	T	T	0	0	0	F	3	low	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
IVR16-g11	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	T	T	T	11	high	0
IVR17-b9	T	T	T	0	F	T	0	0	0	0	0	4	low	0	0	T	0	T	T	0	0	0	0	0	3	low	-1

Figure D.9: IVR pre-test and post-test scores.

PVR condition - participant scores

	PRE-test													POST-test													
id	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	change
PVR01-b10	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	T	T	T	11	high	0
PVR02-b9	T	F	F	0	F	T	0	F	F	0	0	2	low	F	T	F	0	F	T	F	F	0	F	0	2	low	0
PVR03-b10	T	0	0	0	F	T	0	0	0	F	F	2	low	F	0	0	0	F	T	0	0	0	F	F	1	low	-1
PVR04-b9	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	0	T	T	10	high	-1
PVR05-b9	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	T	T	T	T	T	T	T	T	11	high	0
PVR06-b8	T	T	0	0	T	T	0	0	0	0	0	4	low	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
PVR07-b9	T	T	T	T	T	T	T	T	T	T	T	11	high	T	T	T	F	T	T	T	T	T	T	T	10	high	-1
PVR08-b8	T	T	T	T	T	T	T	T	T	T	F	10	high	T	T	T	T	T	T	T	0	0	T	T	9	medium	-1
PVR09-g8	T	F	F	F	F	F	F	F	F	0	0	1	low	T	0	0	0	F	F	0	0	0	F	0	1	low	0
PVR10-g9	T	T	F	0	F	T	0	0	0	0	0	3	low	T	T	T	F	F	F	0	0	0	0	0	3	low	0
PVR11-b12	T	T	T	T	F	F	T	T	T	T	F	8	medium	T	T	T	T	T	T	F	T	T	T	T	10	high	1
PVR12-g8	T	0	T	0	F	F	F	F	F	0	F	2	low	F	T	T	0	F	F	T	T	T	F	0	5	low	1
PVR13-g9	T	F	T	0	F	F	T	T	T	T	T	7	medium	T	T	T	0	T	T	T	T	T	T	T	10	high	1
PVR14-g10	T	T	T	F	F	F	T	T	T	T	F	7	medium	T	T	T	F	F	T	T	T	T	T	F	8	medium	1

Figure D.10: PVR pre-test and post-test scores.

LEGO condition - participant scores

	PRE-test													POST-test													
id	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	A1	A2	A3	A4	A5a	A5b	A6	A7a	A7b	A8	A9	Total T	Aptitude	change
lego01-b11	T	F	F	F	F	T	T	T	T	T	F	6	low	F	T	T	F	F	F	T	T	T	T	T	6	low	0
lego02-b12	T	F	F	F	F	T	T	T	T	F	F	5	low	F	T	F	T	F	F	T	T	T	T	T	7	medium	1
lego03-g12	T	F	F	F	F	F	T	T	T	T	F	5	low	F	T	F	F	F	F	T	T	T	T	T	6	low	1
lego04-g13	T	T	T	F	T	F	T	T	T	F	F	7	medium	F	F	T	F	T	F	T	T	T	F	T	6	low	-1
lego05-g11	T	T	T	F	T	F	T	T	T	F	F	7	medium	F	T	F	F	F	F	T	T	T	T	T	6	low	-1
lego06-b11	T	T	T	F	T	T	T	F	F	F	F	6	low	F	T	T	F	T	T	T	F	F	F	T	6	low	0
lego07-b11	T	T	T	F	T	T	T	T	T	F	F	9	medium	F	T	T	T	T	T	T	T	T	T	T	10	high	1
lego08-b12	T	F	T	F	F	T	F	F	F	F	F	3	low	F	F	T	F	T	T	T	T	T	F	T	7	medium	1
lego09-g11	T	F	T	F	F	F	F	F	F	F	F	2	low	T	T	T	T	T	F	T	F	F	F	F	6	low	1
lego10-b12	T	F	T	F	T	F	T	T	T	F	F	6	low	T	T	T	T	T	T	T	T	T	T	T	11	high	1
lego11-g12	T	F	T	F	T	F	T	T	T	F	F	6	low	T	T	T	T	T	F	T	T	T	T	T	10	high	1
lego12-g12	T	T	T	T	T	T	T	T	T	T	F	10	high	T	T	T	T	T	T	T	T	T	T	F	10	high	0
lego13-b12	T	F	F	F	T	F	F	F	F	F	F	2	low	T	F	T	F	F	T	T	F	F	F	T	5	low	1
lego14-b12	T	F	F	F	T	F	F	F	F	F	F	2	low	T	F	T	F	T	T	T	F	F	F	T	6	low	1
lego15-g12	T	F	T	F	T	F	T	F	T	F	F	5	low	F	T	T	F	T	F	T	T	T	F	T	7	medium	1
lego16-g11	T	F	T	F	T	F	T	T	T	F	F	6	low	T	T	T	F	F	F	T	T	T	F	T	7	medium	1
lego17-g11	T	F	T	T	T	F	T	T	T	F	F	7	medium	T	T	T	T	T	F	T	T	0	F	T	8	medium	1
lego18-g12	F	F	F	F	T	F	F	F	F	F	F	1	low	F	T	F	T	F	F	F	F	F	T	T	4	low	1
lego19-g12	T	F	T	F	T	F	T	T	T	F	F	6	low	F	F	F	F	T	T	T	T	T	F	T	6	low	0

Figure D.11: LEGO pre-test and post-test scores.

D.4 Excerpt from regression analysis

This section contains an excerpt from the logistic regression analysis log file produced by the Generalised **Linear Interactive Modelling (GLIM) package.**

```
[o] GLIM 4, update 9 for Microsoft Windows Intel  on 17 Jul 2006 at 15:05:47
[o]                  (copyright) 1992 Royal Statistical Society, London
[o]
[i] ? $echo $in 'maria.txt' 132 $echo
[e] $units 50
[e] $data
[e] condition gender age yearinschool computer gameplay precorrect postcorrect
[e] $read
[e] 1 0 11 6 3 4 9 9
[e] 1 1 12 6 3 3 7 7
[e] 1 0 9 4 2 3 2 0
[e] 1 0 12 6 3 2 11 11
[e] 1 1 12 6 4 4 11 11
[e] 1 0 10 6 4 4 10 10
[e] 1 0 11 6 3 2 8 11
[e] 1 1 9 3 3 3 5 4
[e] 1 1 9 5 3 2 2 6
[e] 1 0 8 4 4 4 4 5
[e] 1 1 10 6 4 4 7 9
[e] 1 1 10 6 4 2 6 6
[e] 1 1 10 5 4 4 5 9
[e] 1 0 10 5 3 3 7 10
[e] 1 1 8 3 3 3 3 0
[e] 1 1 11 6 4 2 11 11
[e] 1 0 9 4 2 2 4 3
[e] 2 0 10 6 4 4 11 11
[e] 2 0 9 5 2 2 2 2
[e] 2 0 10 6 2 2 2 1
[e] 2 0 9 5 3 4 11 10
[e] 2 0 9 5 3 2 11 11
[e] 2 0 8 3 3 4 4 0
[e] 2 0 9 4 0 0 11 10
[e] 2 0 8 4 3 2 10 9
[e] 2 1 8 4 3 2 1 1
[e] 2 1 9 4 0 0 3 3
[e] 2 0 12 5 3 4 8 10
[e] 2 1 8 4 3 4 2 5
[e] 2 1 9 5 2 2 7 10
[e] 2 1 10 6 2 2 7 8
[e] 3 0 11 6 1 1 6 6
[e] 3 0 12 6 4 2 5 7
[e] 3 1 12 6 1 1 5 6
[e] 3 1 11 6 4 2 7 6
[e] 3 0 11 6 4 1 6 6
[e] 3 0 11 6 2 2 9 10
[e] 3 0 12 6 1 1 2 5
[e] 3 1 12 6 2 1 7 6
[e] 3 0 12 6 4 4 2 6
[e] 3 0 12 6 3 2 3 7
[e] 3 0 12 6 3 4 6 11
[e] 3 1 11 6 4 4 6 7
[e] 3 1 12 6 1 0 1 4
[e] 3 1 11 6 4 4 6 6
[e] 3 1 11 6 1 0 2 6
[e] 3 1 11 6 3 2 7 8
[e] 3 1 12 6 4 2 6 10
[e] 3 1 12 6 1 2 5 7
[e] 3 1 12 6 1 1 10 10
[e]
[e] $factor condition 3
[e] $cal n = 11$
[e]
[e] $data preattempt postattempt
[e] $read
[e] 11 11
[e] 11 11
[e] 4 2
[e] 11 11
```

```
[e] 11 11
[e] 11 11
[e] 11 11
[e] 6 6
[e] 6 9
[e] 10 11
[e] 11 10
[e] 10 11
[e] 8 11
[e] 11 11
[e] 5 0
[e] 11 11
[e] 5 3
[e] 11 11
[e] 7 8
[e] 5 5
[e] 11 10
[e] 11 11
[e] 4 0
[e] 11 11
[e] 11 9
[e] 9 4
[e] 5 6
[e] 11 11
[e] 8 9
[e] 10 10
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[e] 11 11
[e]
[e]
[e] $print 'reached here'$
[o] reached here
[e] $finish
[i] $ECH? $yvar postcorrect $error b n$
[i] ? $eliminate age$


[i] ? $fit precorrect*condition+yearinschool$
[o] scaled deviance =  70.611 at cycle 4
[o]     residual df =  42
[o]
[i] ? $d e$
[o]          estimate        s.e.      parameter
[o]     1     -4.519        1.267      1
[o]     2      0.4286       0.1045     PRECORRE
[o]     3     -0.3627       0.7013     CONDITIO(2)
[o]     4      0.8284       0.9056     CONDITIO(3)
[o]     5      0.4253       0.2081     YEARINSC
[o]     6      0.04953      0.1220     CONDITIO(2).PRECORRE
[o]     7     -0.2184       0.1265     CONDITIO(3).PRECORRE
```

```
[o] scale parameter 1.000
[o]     eliminated term: AGE
[o]
[i] ? $fit -condition.precorrect$
[o] scaled deviance =  78.634 (change =   +8.023) at cycle 4
[o]     residual df =  44     (change =   +2     )
[o]
[i] ? So this results in increase in deviance which is sig. at about 2%
[i] $COM? $fit +condition.precorrect$
[o] scaled deviance =  70.611 (change =   -8.023) at cycle 4
[o]     residual df =  42     (change =   -2     )
[o]
[i] ? $d e$
[o]           estimate        s.e.     parameter
[o]      1      -4.518       1.267      1
[o]      2       0.4286     0.1045      PRECORRE
[o]      3     -0.3827      0.7013      CONDITIO(2)
[o]      4      0.8284      0.9056      CONDITIO(3)
[o]      5      0.4253      0.2081      YEARINSC
[o]      6     0.04953      0.1220      CONDITIO(2).PRECORRE
[o]      7     -0.2184      0.1265      CONDITIO(3).PRECORRE
[o] scale parameter 1.000
[o]     eliminated term: AGE
[o]
[i] ? So now we will rearrange the model to show the intercept and slopes$
[i] ? $fit -1 - precorrect$
[o] scaled deviance =  70.611 (change =    0.) at cycle 4
[o]     residual df =  42     (change =    0 )
[o]
[i] ? $d e$
[o]           estimate        s.e.     parameter
[o]      1      -4.518       1.267      CONDITIO(1)
[o]      2      -4.901       1.407      CONDITIO(2)
[o]      3      -3.690       1.851      CONDITIO(3)
[o]      4      0.4253      0.2081      YEARINSC
[o]      5      0.4286      0.1045      CONDITIO(1).PRECORRE
[o]      6      0.4781     0.07094      CONDITIO(2).PRECORRE
[o]      7      0.2102     0.06609      CONDITIO(3).PRECORRE
[o] scale parameter 1.000
[o]     eliminated term: AGE
[o]
[i] ? So so the equation for condition 1 is:
[i] $COM? -4.518 + 0.4286*precorrect
[i] $COM? -4.901 + 0.4781*precorrect [condition 2]
[i] $COM? -3.690 + 0.2102*precorrect [condition 3]
[i] $COM? note that 1 and 2 are almost the same, whereas 3 has about half the
[i] $COM? slope$
[i] ? $stop
```

D.5 Video transcription

A total of **50** hours of video containing the experience and interviews of the participants in all three treatments, were transcribed by the author. Despite the manual labour that this entailed, it was considered important for the research, as it helped maintain familiarity with the data. As verbal data tend to be voluminous, especially when transcription must include accompanying gestures and activity, the resulting transcripts consisted of several pages per participant. The video transcription was conducted with the help of the Transana 2.05 software, a free transcription tool, developed at the Wisconsin Center for Education Research, University of Wisconsin, Madison (Figure D.12).

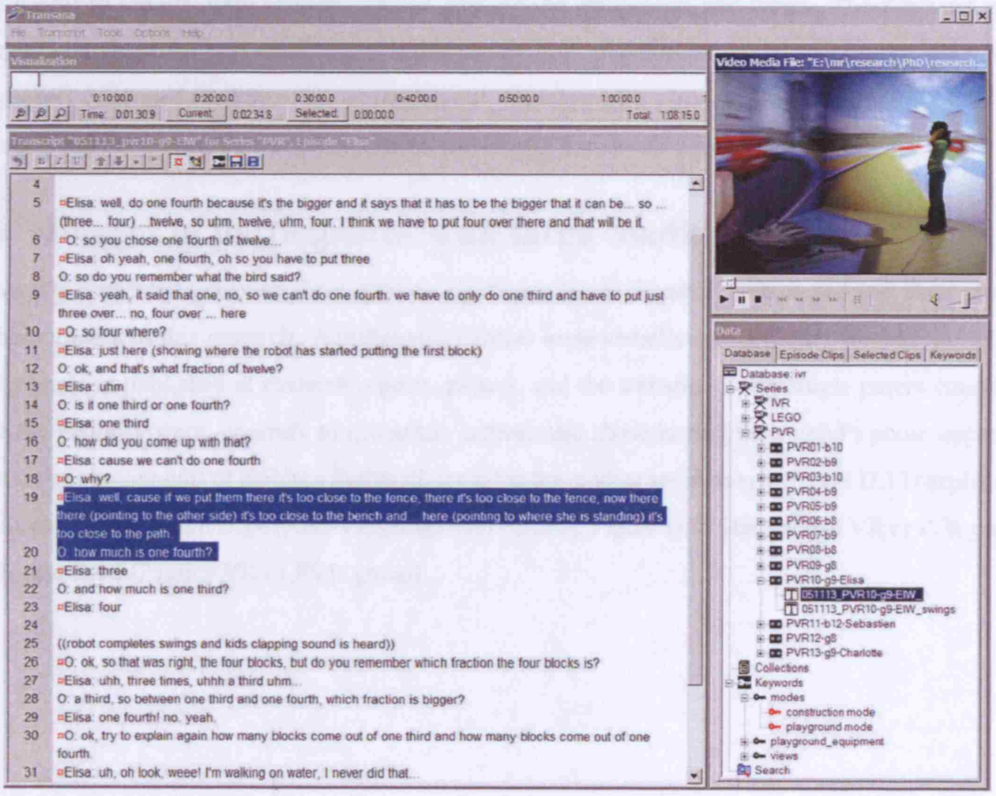

Figure D.12: A view of the Transana 2.05 interface, a free transcription software developed by the Wisconsin Center for Education Research, University of Wisconsin, Madison, http://www.transana.org.

Transana uses a classification scheme which divides video data into Series, Records, Episodes, Transcripts, Collections, and Clips. A Series is a group of related video files -in this case, the three experiment conditions, Interactive VR (IVR), Passive VR (PVR), and Non-VR (LEGO), formed three Series of video files. Within a Series are records for one or more video files, which are called Episodes. Each video file must have a separate Episode definition while each Episode can contain one or more Transcripts. For this research, each participant formed one Episode and each Episode included one Transcript. However, there may be cases where field notes are stored as one transcript, a verbatim transcription as a second transcript, and a Jeffersonian-annotated transcription including information about phoneme pronunciation, non-word utterances, pauses, and gestures as a third transcript, each for its own unique analysis.

Additionally, Transana helps organise the analysis by providing support for Collections. A Collection is a group of conceptually-related video segments taken from the Episodes. Collections are usually named for the common analytic theme that one is trying to analyse by looking at the related video clips. Within a Collection are records for one or more analytically-interesting portions of Episodes, which are known as Clips. The bulk of the analytic work is done at the Clip level.

A Keyword Group is a group of related Keywords. Keywords can be assigned to Episodes and Clips to describe the analytically-interesting content of the associated video. Keywords may contain Example Clips. These clips should show clear examples of what is meant by the keyword. In this case, three Keyword Groups were created: modes, playground equipment, and views. The Keyword group "modes" contained the keywords 'construction mode' and 'playground mode', the group "playground equipment" contained the keywords 'crawl tunnel', 'monkey bars', 'roundabout', 'sandpit', 'slide', and 'swings', and the group "views" contained the keywords 'top-down' and 'ground'.

D.6 Images of participants in all three conditions

All parents consented to having their children's participation in the study videotaped and photographed for the purposes of this research. Additionally, parents were verbally asked if they would mind if their child's photo is published in research reports, papers, and the website. Every single parent consented, while the majority were -contrary to concerns- enthusiastic about having their child's photo appear. A selection of photographs of children that participated in the studies are shown in Figure D.13 (exploratory and pilot studies), Figure D.14 (Non-VR group with LEGO), Figure D.15 (Interactive VR or IVR group), and Figure D.16 (Passive VR or PVR group).

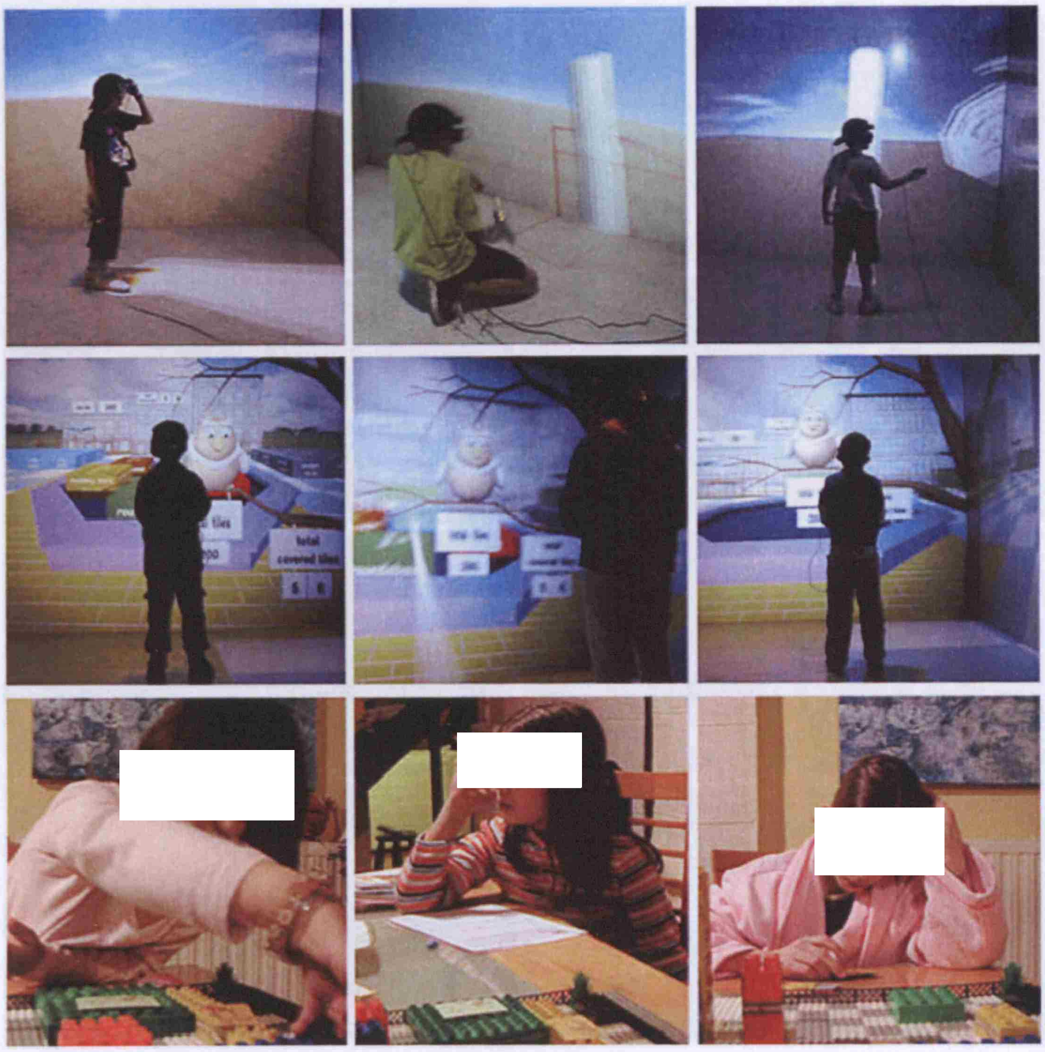

Figure D.13: The children that took part in the exploratory study (top row) and the piloting phase of the main study.

Figure D.14: Some of the 19 children that took part in the non-VR group pictured here while completing the tasks of the LEGO playground activity.

Figure D.15: Some of the 17 children that took part in the interactive VR (IVR) activity pictured here as they interact in the Virtual Playground.

Figure D.16: Some of the children that took part in the passive VR (PVR) activity pictured here as they watch and guide the robot in performing tasks in the Virtual Playground.

D.7 Sample of observation transcripts

This section contains an excerpt from the combined transcript and computer log file of a participant in the IVR condition. The merging of the transcript and log file was completed by juxtaposing the two files during the transcription process in Transana. All logfile notes are bold and italicized.

Observation transcript and logfile, page 4/6

Participant ID: IVR11-g10

Date: Saturday, June 11, 2005

Task: swings

[***logfile: At 24 mins 12 sec clicks on red bird***]

[*red bird completes telling rule*]

O.: So what do you have to do?

Annie: They're not big enough, have to make them one third bigger or one fourth bigger whichever covers more area.

O.: Ok, so how big are they now?

Annie: Uhm. Twelve.

Annie: I need to uhm a third of [*thinking*]

O.: So you have to choose between a third of or a fourth, which are you going to choose?

Annie: A fourth. Which is... three. No...

Annie: I'll try three.

[*picks up one block, looks and then tries to put it on the side of sandpit where three empty tiles are available*]

[***logfile: Received forbidden_onbench feedback at time 26 mins 13 secs***]

[*goes to other side where three tiles are available*]

[***logfile: Received forbidden_next2fence feedback at time 26 mins 15 secs***]

[***logfile: Received forbidden_next2fence feedback at time 26 mins 18 secs***]

Annie: Hmm.

[*Places block on an empty tile*]

[*Then starts moving existing blocks around to change the layout and leave space on the side of the fence*]

[*Picks another block from pool*]

O.: So how many are you adding?

Observation transcript and logfile, page 5/6

Participant ID: IVR11-g10

Date: Saturday, June 11, 2005

Task: swings

Annie: Three. [*picks third block from pool and puts it on the ground*]

[*Clicks on red button*]

[*logfile: At 27 mins 56 secs switched to object mode*]

Annie: It's wrong.

O.: Why?

Annie: Hmph.

O.: Three is one fourth. Is that what you decided?

Annie: Yeah.

O.: What was the other option?

Annie: One third.

Annie: Uhm. Maybe I need to put down four. I think. Uhm... Yeah, four.

[*goes to pool and picks one more. Clicks on the red button*]

[*logfile: At 28 mins 2 secs switched to object mode*]

[*The layout she has made does not have any space for it*]

Annie: I don't know where to put it.

O.: Did you change the layout?

[*starts taking away blocks and putting them back in the pool*]

O.: Why did you change the layout before?

Annie: Because I couldn't get any more blocks in cause it was too near the fence.

[*trying to put near the sandpit again*]

Annie: No. [*goes to other side and successfully places block where she had taken away before*]

Annie: I think I need to change the layout.

O.: Why is that?

Annie: Because it doesn't really... It looks a bit funny

O.: So how would you change it?

Annie: Uhm

Observation transcript and logfile, page 6/6

Participant ID: IVR11-g10

Date: Saturday, June 11, 2005

Task: swings

[*starts moving blocks around and brings it back to its original shape plus the four new blocks*]

[*clicks on red button. The blocks turn into swings*]

[*logfile: At 31 mins 18 secs switched to object mode*]

[*logfile: At 31 mins 18 secs successfully completed and switched to object swing*]

[*logfile: Manipulated red cubes for 7 mins 8 secs*]

[*logfile: Manipulated 27 cubes of color red*]

O.: So what was the correct answer here?

Annie: Uhm. A third which is four blocks.

O.: You didn't think about it from the beginning though, how come?

Annie: Uhm. Cause I knew what one fourth was and I didn't have to work it out.

[*meaning that she tried the easiest solution that came to her mind right away*]

Received 7 occupied feedback

Received 3 adjacent feedback

Received 2 forbidden_onbench feedback

Received 5 forbidden_next2fence

Received 3 forbidden_onpath feedback

Total time elapsed 33 mins 59 sec

Appendix E

Approved Ethics Application

A full application for ethical approval and the Data Protection Act were submitted to the University College London's Committee on the Ethics of non-NHS Human Research in January 2004 and approved in April 2004 (No. 0171/001) for one year. The approval was renewed for an additional year (April 2005 - April 2006). An extract of the application is included below. The letter, information sheets, and informed consent form to parents can be found in Appendix C.

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05 April 2004

Ms Maria Roussou
Department of Computer Science
UCL

Dear Ms Roussou

Re: Notification of Ethical Approval

Project ID: 0171/001: Interactivity and Learning: the study of young learners' activity within interactive virtual environments

Further to the extra information that you submitted to the Committee on 1 April 2004, the above research has been given ethical approval following review by the Vice-Chair of the UCL Committee for the Ethics of non-NHS Human Research for the duration of the project (1 April 2004 – 1 April 2005) subject to the following conditions:

1. You must seek Chair's approval for proposed amendments to the research for which this approval has been given. Ethical approval is specific to this project and must not be treated as applicable to research of a similar nature. Each research project is reviewed separately and if there are significant changes to the research protocol you should seek confirmation of continued ethical approval by completing the 'Amendment Approval Request Form'.

The form identified above can be accessed by logging on to the ethics website homepage: http://www.grad.ucl.ac.uk/ethics/ and clicking on the button marked 'Key Responsibilities of the Researcher Following Approval'.

2. It is your responsibility to report to the Committee any unanticipated problems or adverse events involving risks to participants or others. Both non-serious and serious adverse events must be reported.

Reporting Non-Serious Adverse Events
For non-serious adverse events you will need to inform Ms Helen Dougal, Ethics Committee Administrator (h.dougal@ucl.ac.uk), within ten days of an adverse incident occurring and provide a full written report that should include any amendments to the participant information sheet and study protocol. The Chair or Vice-Chair of the Ethics Committee will confirm that the incident is non-serious and report to the Committee at the next meeting. The final view of the Committee will be communicated to you

SECTION B: DETAILS OF THE PROJECT

B1. Please provide a brief summary of the project in lay terms (if a Class Research Project as defined on page 1, please include aims and objectives of the course) including the hypothesis to be tested if relevant (max 200 words).

The proposed research aims to study the value of user interaction in Virtual Reality (VR) educational environments in enhancing conceptual learning of a subject matter. Specifically, the purpose is to evaluate if children learn better by interacting in (i.e. exploring, reacting to, and acting upon) an immersive virtual environment (VE). The VR technology used for the study will be the CAVE, a room made up of projection screens displaying computer-generated moving images in which the user interacts with the use of a joystick. The participants will be primary school students between the ages of 7 and 11 who will be asked to complete a learning task related to the concept of mathematical 'fractions'. The participants will be assigned to one of three groups: (I) a control group that will perform a task on paper (II) an experimental group that will view the task being performed in a VE but will not have the ability to interact and (III) an experimental group that will perform the task in a VE with full ability to interact (navigate, select and manipulate virtual objects). Pre-tests, post-tests and an interview will be carried out to measure the children's knowledge of the subject matter.

B2. Briefly characterise in lay terms the research protocol, type of procedure and/or research methodology (e.g. observational, survey research, experimental). Give details of any samples or measurements to be taken (max 1500 words)

The purpose of this study is to evaluate how children interact and learn in a virtual environment. Hence an experimental procedure will be carried out, which includes a set of pilot and main studies. The children will be engaged in activities, such as designing a playground, which will require that they make mental calculations in the form of fractions operations, in order to meet the design parameters given by the system. The research will focus on the children's ability to accomplish the various cognitive (conceptual) tasks and the ability to transfer their actions. Pre-tests, post-tests and an interview will be carried out. The total duration of the study is estimated to approximately 2 hours for each participant including 5-minute breaks during the virtual reality session (every 10 minutes) for those participants that will be assigned to a task in VR.

Experimental Procedure

Each study will be conducted with one participant at a time. The duration of the study will be 2 hours for each child. The nature of the study is such that the child will be free to interact with the virtual world. The study will take place at the University College London's Department of Computer Science and the child will be inside the laboratory (in different rooms) for the duration of the study. The VR technology used for the experiment is called a CAVE. The CAVE (CAVE Automatic Virtual Environment) is a room-sized virtual reality system constructed of three translucent walls and a floor, onto which high-resolution computer-generated stereoscopic images are projected. The user views the projected stereoscopic images by wearing a pair of light-weight plastic shutter glasses and can move around freely to interact with the environment by using a simple interaction device, similar to a mouse, which contains a joystick and buttons. It is used to navigate around the virtual world, and to select and manipulate virtual objects within that world.

In the first part of the study, the participant will be asked to fill out a questionnaire with math questions similar to those asked in the Key Stage 2 SAT math test. This part of the study will take place in the classroom a few days before the experiments in the laboratory. After all questionnaires have been collected, each child will be assigned to one of three groups, either the control group, or one of the two experimental groups, in an even spread according to aptitude, gender, and condition.

If assigned to the control group, the participant will take part in an activity on paper using coloured stickers and/or colouring pencils. The activity will involve the design of a playground on a grid-like floor plan. The different stickers will represent the swings, slides, etc., which the participant must position and resize according to the requirements/specifications provided. This group will not perform the task in a digital environment. Each participant will be actively involved in designing the playground, however no interactivity (system feedback) will exist.

If assigned to an experimental group, the participant will take part in a similar activity in the CAVE. In other words, the participant will be immersed in a 3D re-construction of a playground in virtual reality and may be asked to design the playground in this 3D space. Two possibilities exist here: the participant will either be assigned to a "passive VR" experience, where the re-design of the playground is played out as in a video without allowing the participant to act, or to an "interactive VR experience" where the participant actively designs the playground, having full control over the interactive features of the system. In this case, the task will be explained to the participant who will have a chance to practise moving objects around in the virtual space before starting. The task will be similar to playing with a virtual construction kit (such as LEGO®) or a computer game but will not contain fast action or violence. The experience will require that the child actively explores the virtual surroundings and explains her/his actions to the observer.

In all three cases (activity on paper, passive experience in VR, and activity in VR), the participant will be asked to complete a post-test with questions related to fractions, similar to the pre-test. Finally, every child will be interviewed about his/her experience by the researcher.

<u>Methods</u>
Overall, the experiments will involve observation, written questionnaires and an open-ended interview. The observation methods include video and audio recording of the participant. Each participant taking part in the virtual reality activity will wear a pair of lightweight plastic glasses (which can be worn over eyeglasses if necessary) and will use a handheld device with a joystick and buttons for moving the virtual building blocks around. A small lavaliere microphone will also be attached to the participant for recording her/his voice when speaking. The duration of the pre-test, the actual task, and the post-test will be approximately 30 minutes each. Specifically for participants of the VR task, three short breaks will be taken during the experience (every 10 minutes). The researcher will interview each participant after the study. The interviews will be of informal nature and will ask for the child's impressions about the VR experience. The duration of the interview will not exceed 15 minutes. The total duration of the experiment for each participant, including training, pre-test, task, post-test, and interview is estimated at approximately 2 hours.

<u>Methodology for Analysis</u>
The method of analysis will be based on supporting or refuting emerging hypotheses, we will review the video of all sessions and identify various points where interesting interactions seem to occur (Barab et al., 1999). We will then propose hypotheses concerning the interactions observed, explaining these in terms of learning. We plan to focus on points where participants make a statement that indicate they have changed their belief or where we can come to conclusions from our observation of the subject's behaviour in the environment. The collected data will be analysed using an Activity Theory framework (Nardi, 1996). Activity Theory provides us with the conceptual vocabulary to help interpret these points qualitatively. All participants mentioned during the analysis will be pseudo-anonymised.

Barab, S.A. Hay, K.E., and Barnett, M.G. Virtual solar system project: Building understanding through model building. *Annual Meeting of the American Educational Research Association*, Montreal, Canada, AERA 1999.

Nardi, B. A *Context and Consciousness: Activity Theory and Human-Computer Interaction*. MIT Press, Cambridge, Massachusetts, 1996.

Attach any questionnaires, psychological tests, etc...(a standardised questionnaire does not need to be attached, but please provide the name and details of the questionnaire together with a published reference to its prior usage).

A sample of the questions given in the pre- and post-tests is attached to the parent consent form. Each questionnaire will include approximately 15 questions.

B3. In lay terms state the intended value of the project, giving necessary scientific background. (max 500 words)

The main research question of this study examines the effect that 'interactivity', as one of the essential properties of a computer-based learning environment, may have in the formation of children's conceptual learning. The computer-based environment examined is a virtual environment. Virtual Reality (VR), regarded here as the three-dimensional multi-sensory immersive and interactive digital environment, has triggered public imagination as the dominant technological metaphor for the way our work, education, and leisure may be delivered in the future. While VR has yet to become a widespread technology, there has, in fact, been a proliferation of VR installations (in the form of exhibits) and applications (in the form of 'experiences') available to and accessible by the public. The entertainment market is usually the first to embrace current technological achievements to attract and motivate visitors. Other public settings, such as museums and informal educational institutions, are generally known to be hesitant in adopting cutting-edge digital technologies. However, even these are now considering various forms of VR as a means to attract and motivate visitors but also in an attempt to deliver their educational agenda more effectively (Roussou, 2004). Considering the plethoric development of interactive systems at large, it may not be long before VR installations and applications make their way into the schools and the home.

For these environments, the techniques for developing interactivity, regarded as the process with which users can act upon and even modify a virtual world, are relatively unexplored. Yet, interactivity is being promoted widely, not only for its recreational potential but also for its significance for learning. This is even more prominent in the case of VR, since interactivity is largely regarded as one of the medium's essential properties. The immediate implication which can be drawn from studying related literature is the common belief that the effectiveness of a VE that provides a high degree of interactivity is substantially more than the effectiveness of a VE where interactivity is not present; it is commonly considered that a digital learning environment is more effective if it is interactive. However, little systematic research is available to provide evidence that interactive learning environments in VR can bring "added value" to learning, especially in children. Furthermore, it is not certain if interactivity alone, as an essential property of the virtual reality medium, can provide a strong effect upon learning. Most research in VR is focused on the immersive properties of the medium (the sense of presence it evokes. Similarly, previous research into the use of VR in education has concentrated on training applications rather than conceptual learning. This problem is particularly acute where understanding, not behaviour, is of concern. Hence, this research aims at examining the following central question: does interactivity enable learners to construct meaning?

Roussou, M. Learning through Play. An Exploration of Interactivity in Virtual Environments for Children. *ACM Computers in Entertainment 1*, 2 (2004)

B4. Where will the study take place (please provide name of institution/department)? If the study is to be carried out overseas, what steps have been taken to secure research and ethical permission in the study country? Is the research compliant with Data Protection legislation in the country concerned or is it compliant with the UK Data Protection Act 1998?

Department of Computer Science, University College London

B5. Have collaborating departments or departments (mentioned above) whose resources will be needed been informed and agreed to participate?
(Explain the steps taken to ensure collaboration and attach any relevant correspondence)

No resource implications.

B6. How will the results be disseminated, including communication of results with research participants?
The results of the study will be disseminated in the standard way that PhD research is, through relevant journal and conference publications. Furthermore, the teachers with who continuous

collaboration has been established will be informed of the results of the study that interest them.

SECTION C DETAILS OF PARTICIPANTS

C1. Please state below the number of participants who will be involved in this research:

60

C2. In cases where databases will be used and/or participants will be identified from information held by another party describe the arrangements you intend to make to gain access to this information including necessary ethical approval (see Guidance Note C2).
N/A

C3. Will the research include children or vulnerable adults such as individuals with mental health problems, learning disabilities, prisoners, elderly, young offenders, socially or politically disadvantaged e.g. dissident political groups? YES/NO
YES
The research will include children aged between 7 and 12 years old. The research will not include children with mental health problems, learning disabilities or social disadvantages.

If yes, explain the necessity of involving these individuals as research participants.
The research is aimed at examining conceptual learning. According to Piaget's theory on the cognitive development of humans, children in elementary and early adolescence (the age group we are targeting) are in the concrete operational stage, in which intelligence is demonstrated through logical and systematic manipulation of symbols related to concrete objects and in which operational thinking develops. Hence, we have chosen individuals of this age group in order to best study the development of learning.

If children are to participate, how is the consent of parents or guardians to be obtained? (Please attach a copy of the relevant form)
Parent consent forms will be provided to the parents by the teachers a few weeks before the beginning of the study. The consent forms will include a detailed description of the study with photographs and a form with two sections, which parents will sign, return one section and keep the other for their records. A copy of the letter to the parents is attached.

How is the consent of the child itself to be obtained or ascertained? (Please attach a copy of the relevant form)
Children will be asked if they wish to participate by their teachers and parents. If a child does not wish to participate, then the parents will not sign / provide their consent. If a child wishes to participate but changes his/her mind during the study, then the study will end immediately for that child without further questions.

C4. Will payment or any other incentive, such as a gift service or free services, be made to any research participant? YES/NO
YES

If yes, please specify and state the level of payment to be made and/or the source of the funds/gift/free service to be used.

No payment is foreseen, as participants are children. However, a gift such as a printed photo of the virtual experience, for each student that participated in the experimental study, or crayons and stickers, for each student in the control group (that does not participate in the VR experience), may be given as a "souvenir". A reimbursement for transportation cost to/from UCL is foreseen for the parents who will bring their children.

Please explain the justification for offering payment or other incentive.
A symbolic and costless gift is a small token of appreciation to the children that will participate.

C5. Please specify the method of recruitment. If you are proposing to advertise, please attach a copy of the advert to be used.
(NB. A Data Protection Disclaimer must be included in the wording of any advertisement or web-based recruitment drive).

Participants will be recruited with the help of collaborating teachers. Teachers will be informed of the research process beforehand, including the information that participant number alone will identify all collected questionnaire forms and video material. Teachers will be informed that only the experimenters will have access to information about the true identity of participants. We undertake not to disclose this information to third parties and will keep such details in a secure place. Results will be referred to in statistical form only, or will be pseudo-anonymised.

C6. Will the participants participate on a fully voluntary basis?
YES

Will UCL students be involved as participants in the research project? YES/NO
NO

Please state how you will bring to the attention of the participants their right to withdraw from the study without penalty?
Parents will be informed of their child's right to withdraw through the consent letter (attached). Furthermore, children will be asked (verbally) by the researchers if they wish to participate in the study and will be told (verbally) that they can withdraw at any time.

C7. How will participants be informed of the nature of their research and their participation in it?
(Please provide details of how informed consent is to be obtained) Attach a copy to this application of your participant information sheet, written in simple non-technical language together with a separate copy of your informed consent form which should meet the requirements of the Data Protection Act 1998.

Please view attached letter to parents including a sample of the consent form.

In cases where it is not proposed to obtain the participants informed consent, please explain why below.

C8. Will any form of deception be involved that raises ethical issues? If so, please explain.

NO

C9. Will you provide a full debriefing at the end of the data collection phase? YES/NO

YES, to the extent that it will be possible with children. A full debriefing will be provided to the collaborating teachers.

If 'no', please explain why below.

SECTION D DETAILS OF RISK

D1. Will these participants participate in any activities that may be potentially stressful or harmful in connection with this research? YES/NO
NO

If 'yes', please describe in detail the nature of this risk or stress.
Although rare, participants may suffer from nausea or eye-strain associated with the use of virtual reality equipment. They will be kept under observation and should they feel uncomfortable or unwell for any reason, the experiment will be stopped immediately.

What specific steps will be taken to minimise and monitor this risk or stress?
A precaution will be taken against the risk of epileptic fits induced from exposure to video equipment. Anyone at known risk from an epileptic episode will not be allowed to participate in the experiment. The parent consent form will include a relevant question.

D2. Does the research involve the use of drugs? YES/NO
If 'yes', please refer to Appendix I
NO

Does this project involve the use of genetically modified materials? YES/NO
NO
If 'yes', has approval from the Gene Modification Safety Committee been obtained for work? YES/NO If 'yes', please quote the Gene Modification Reference Number. ....

D3. Will any ionising radioactive substances be used on the research participant(s)? YES/NO
NO
If 'yes', please refer to Appendix II

Will x-rays be used? YES/NO
NO

If 'yes', please refer to Appendix II

D4. Specify whether the following procedures are involved:

Any invasive procedures(s): YES/NO NO **Physical contact:** YES/NO NO
Any procedure that may cause mental distress: YES/NO

NO

Please state briefly any precautions being taken to protect the health and safety of the research participants.

D5. Please note any special or unusual circumstances related to this research, which might give rise to special concern for the welfare of research participants and describe how these special concerns will be addressed. N/A

D6. Please state briefly any precautions being taken to protect the health and safety of researchers and others associated with the project (as distinct from the research participants).

N/A

Appendix F

List of Acronyms

API	Application Program Interface
AR	Augmented Reality
AT	Activity Theory
CAVE	CAVE Automatic Virtual Environment
HCI	Human Computer Interaction
HMD	Head Mounted Display
IVR	Immersive Virtual Reality
MR	Mixed Reality
VE	Virtual Environment
VLE	Virtual Learning Environment
VP	Virtual Playground
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
XP	eXtended Performer
ZPD	Zone of Proximal Development

Appendix G

Related Published Papers

1. Roussou, M., Oliver, M., and Slater, M. (2006, to appear). The Virtual Playground: an Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning. *Journal of Virtual Reality, Special issue on "Using Virtual Reality in Education"*, Springer.

2. Roussou, M., Oliver, M., and Slater, M. (2007, to appear). An Evaluation Methodology for User Interaction in Virtual Environments for Learning. *Journal of Cognition, Technology, and Work, Special issue on "Child Computer Interaction: Methodological Research"*, Springer.

3. Roussou, M. and Slater, M. (2005). *A Virtual Playground for the Study of the Role of Interactivity in Virtual Learning Environments.* In Proceedings of PRESENCE 2005: The 8th Annual International Workshop on Presence, September 21-23, London, UK, pp. 245-253.

4. Roussou, M. (2005). *Can Interactivity in Virtual Environments Enable Conceptual Learning?* In Proceedings of 7th Virtual Reality International Conference (VRIC), First International VR-Learning Seminar, Laval, France, pp. 57-64.

5. Roussou, M. (2004). *The Role of Interactivity in the Formation of Informal Educational Experiences.* In Proceedings of 2nd International Museology Conference, Mytilene, Greece, to appear.

6. Roussou, M. (2004). *Interactivity and Conceptual Learning in Virtual Environments for Children.* In Proceedings of ACM SIGCHI Conference on Human Factors in Computing Systems: Extended Abstracts, Vienna, Austria, pp. 1049-1050.

7. Roussou, M. (2004). *Examining Young Learners' Activity within Interactive Virtual Environments.* In Proceedings of Interaction Design and Children, Maryland, USA, pp. 167-168.

8. Roussou, M. (2004). Learning by Doing and Learning through Play: an Exploration of Interactivity in Virtual Environments for Children. *ACM Computers in Entertainment Journal (CiE)*, 2(1), pp. 1-23.

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